Beam-Based Feedback for the European XFEL

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HELMHOLTZ ASSOCIATION

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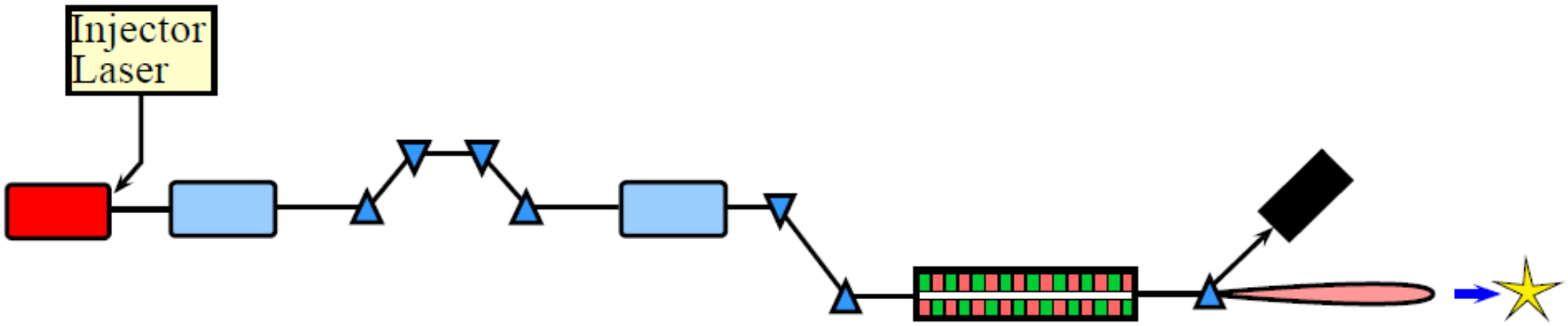
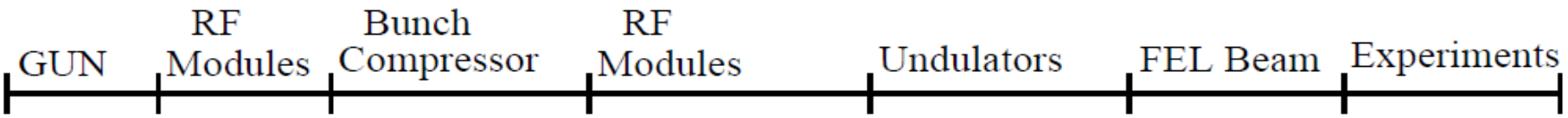
Principle of Free – Electron Laser



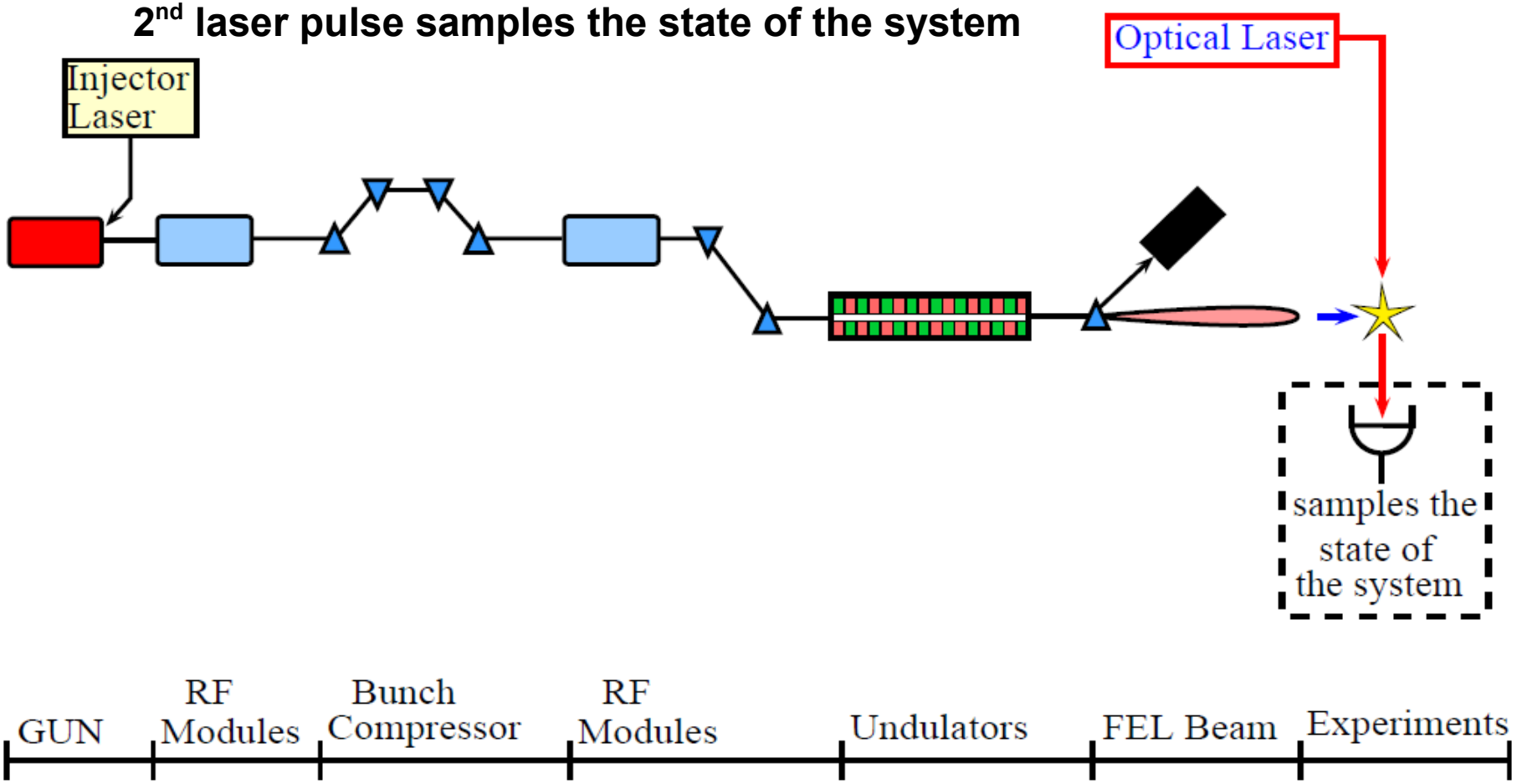


Principle of Free – Electron Laser

Pump-Probe Experiments

FEL pulse excites the sample

2nd laser pulse samples the state of the system

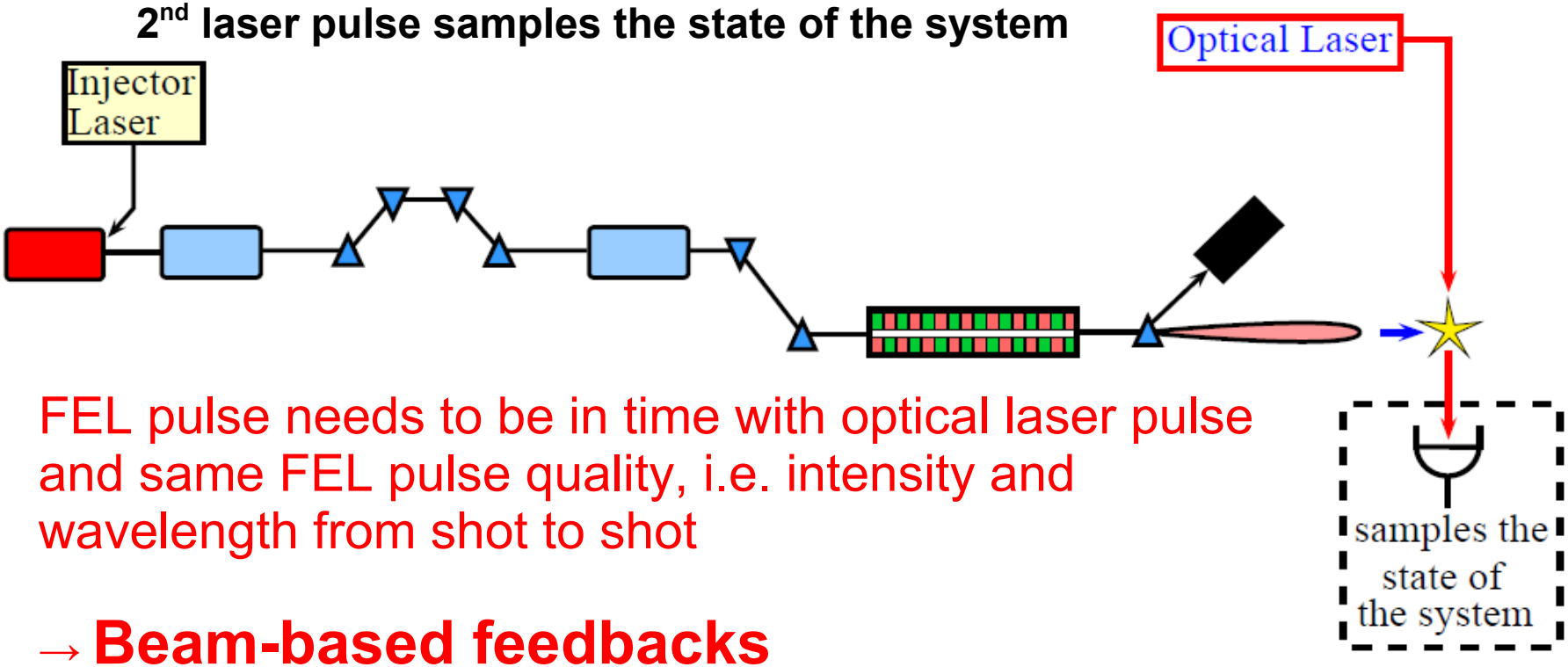


Principle of Free – Electron Laser

Pump-Probe Experiments

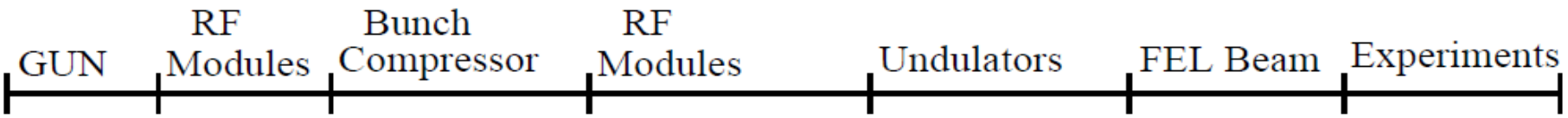
FEL pulse excites the sample

2nd laser pulse samples the state of the system



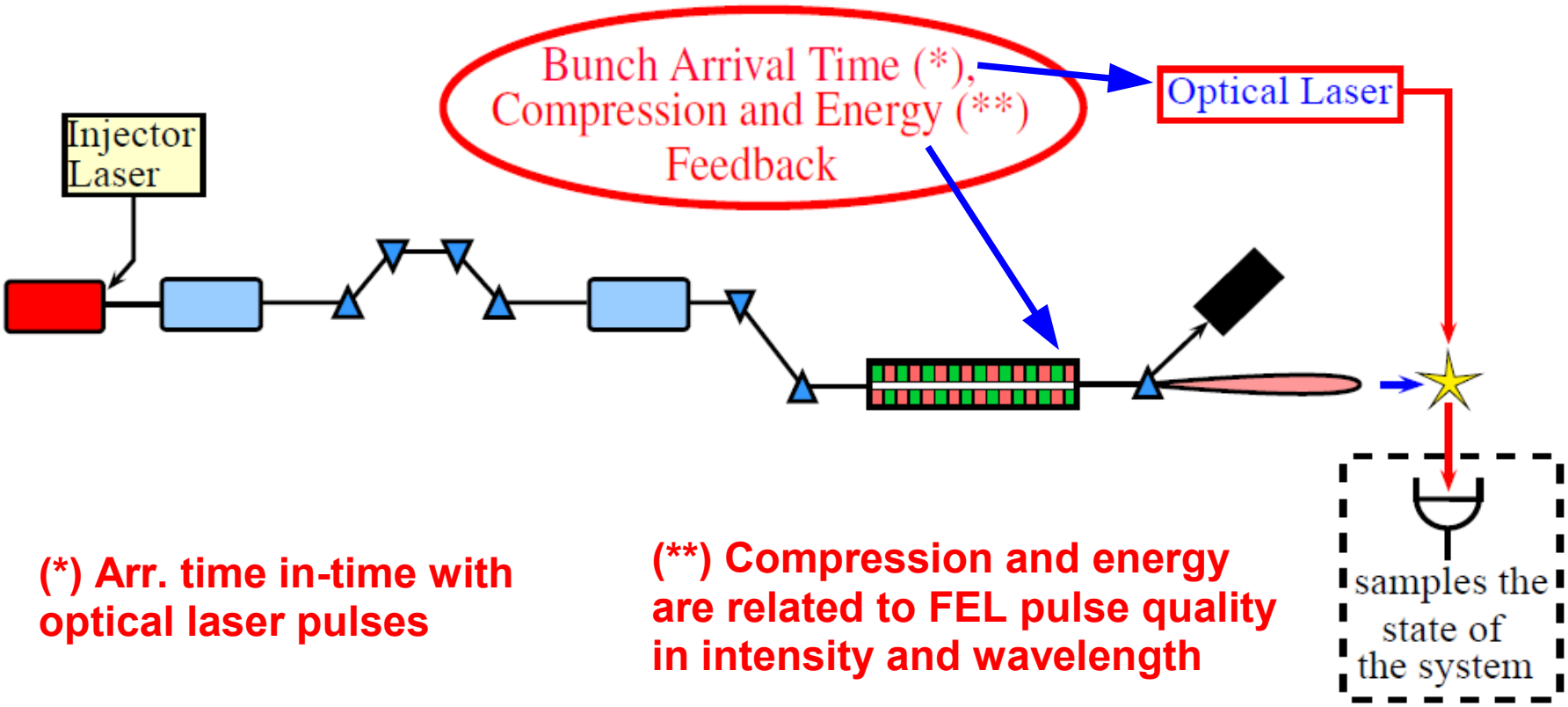
FEL pulse needs to be in time with optical laser pulse and same FEL pulse quality, i.e. intensity and wavelength from shot to shot

→ **Beam-based feedbacks**



Principle of Free – Electron Laser

Beam-based feedback for longitudinal parameters

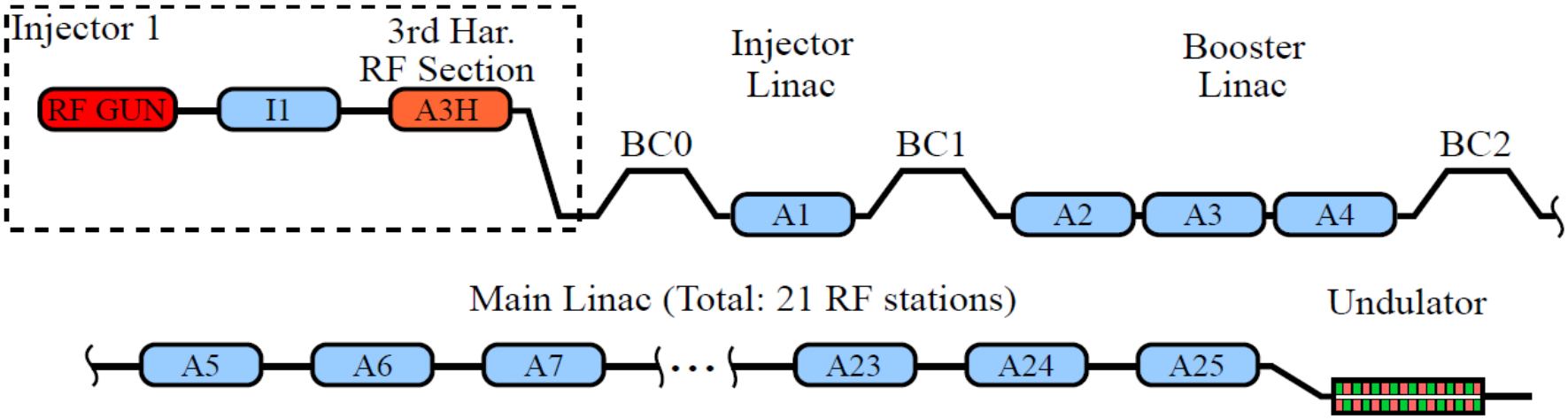


(*) Arr. time in-time with optical laser pulses

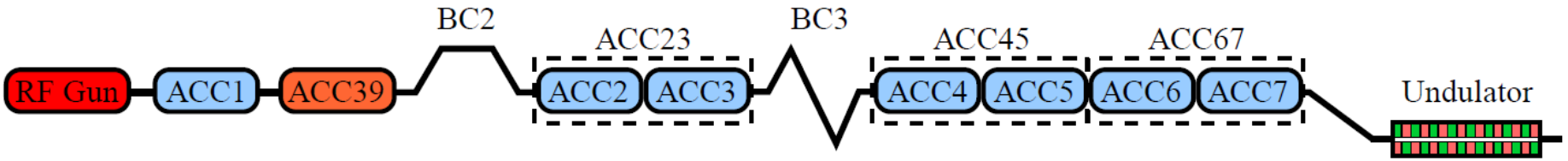
(**) Compression and energy are related to FEL pulse quality in intensity and wavelength

Linear Accelerators at DESY in Hamburg

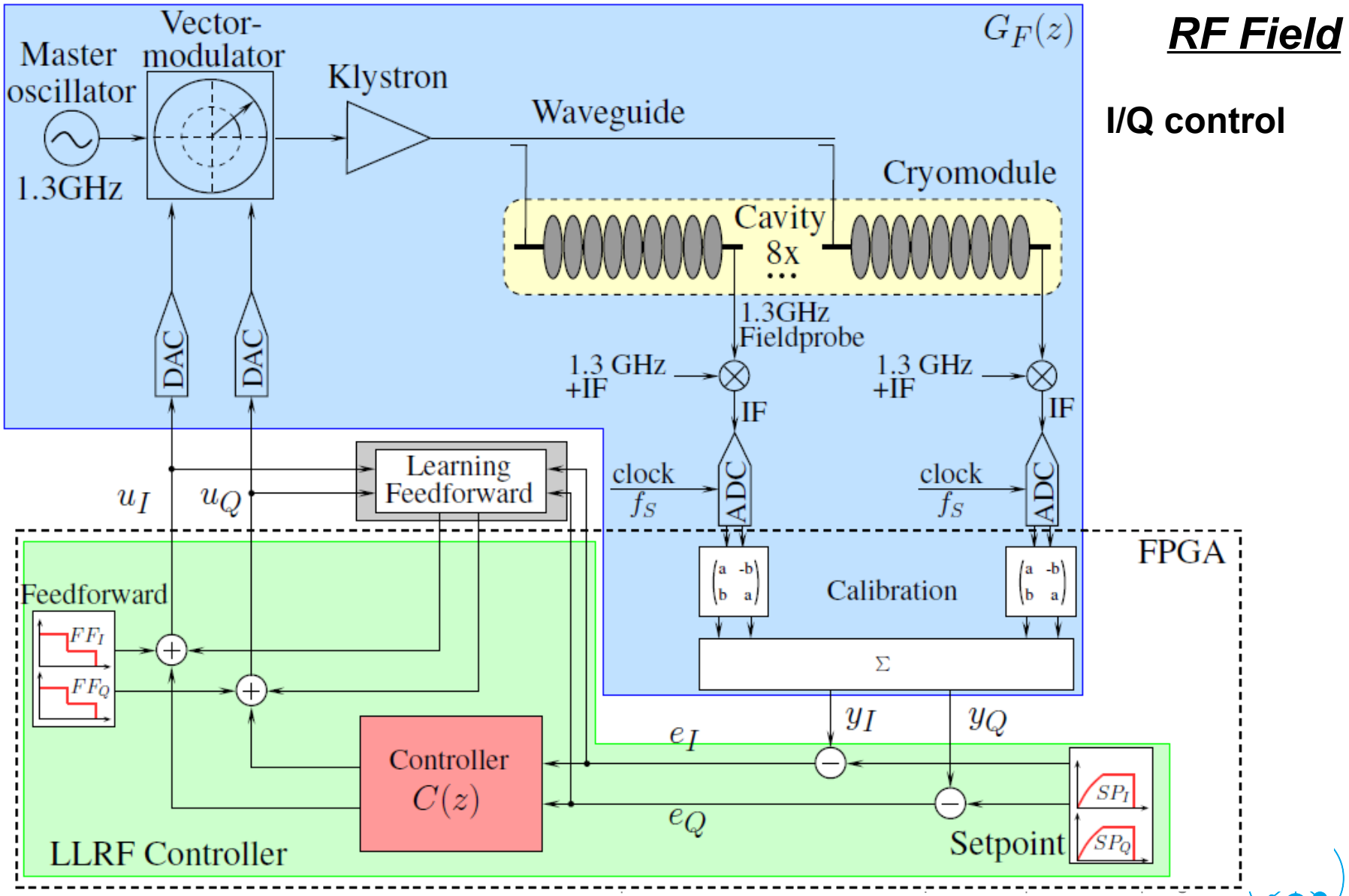
European XFEL – currently under construction



FLASH – in operation (test bench for XFEL)



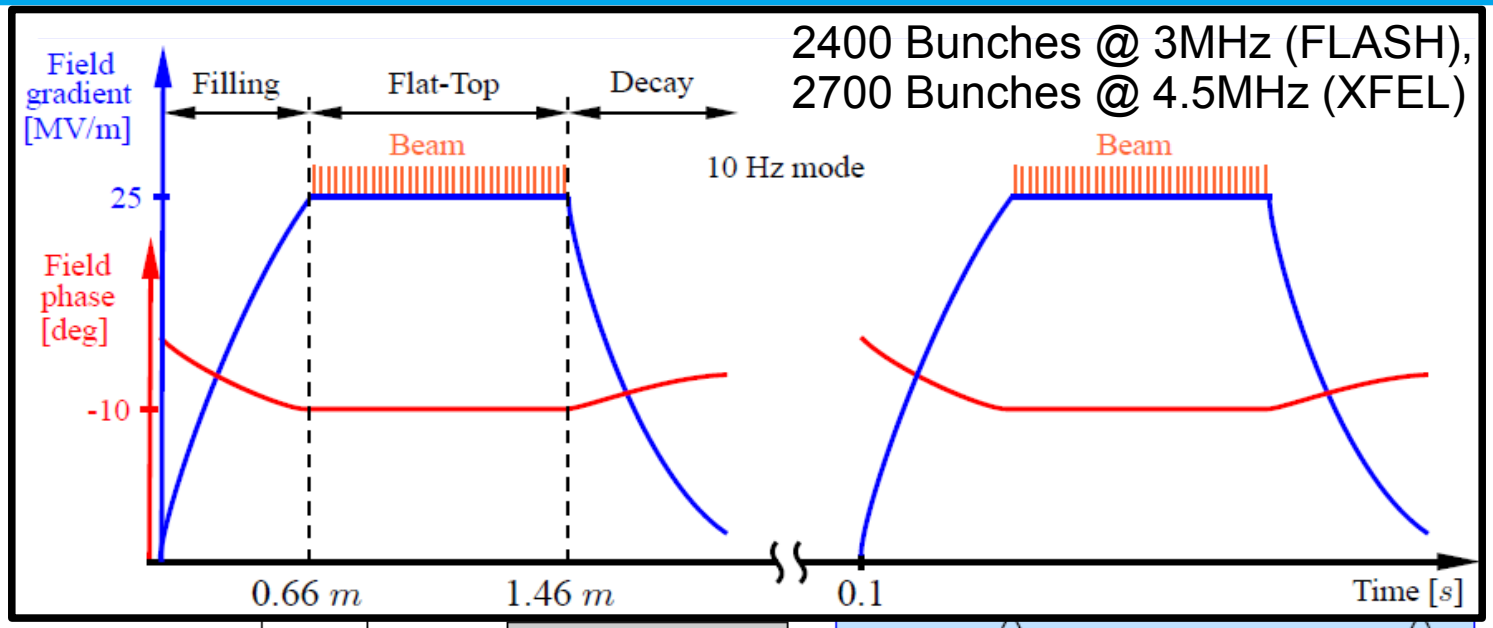
System Overview – FLASH and XFEL



RF Field

I/Q control

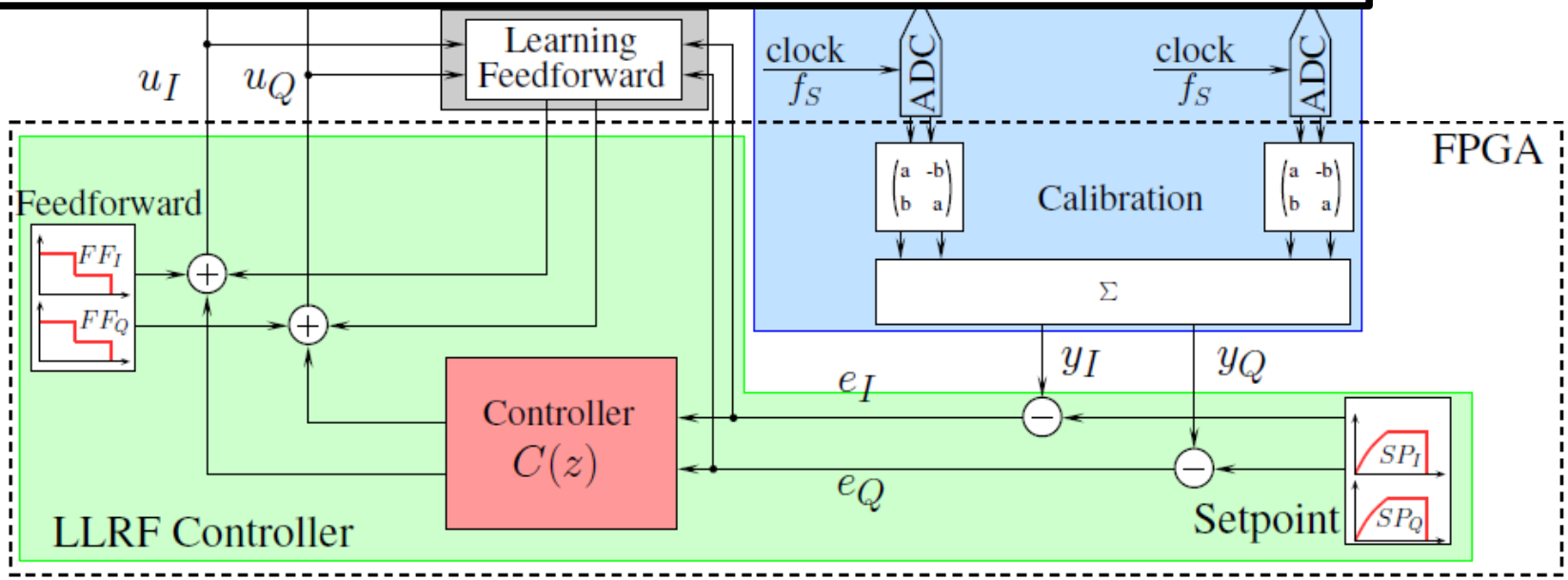
System Overview – FLASH and XFEL



RF Field

I/Q control

Pulsed operation
10 Hz
2ms pulse length
(Filling, Flattop and Decay)



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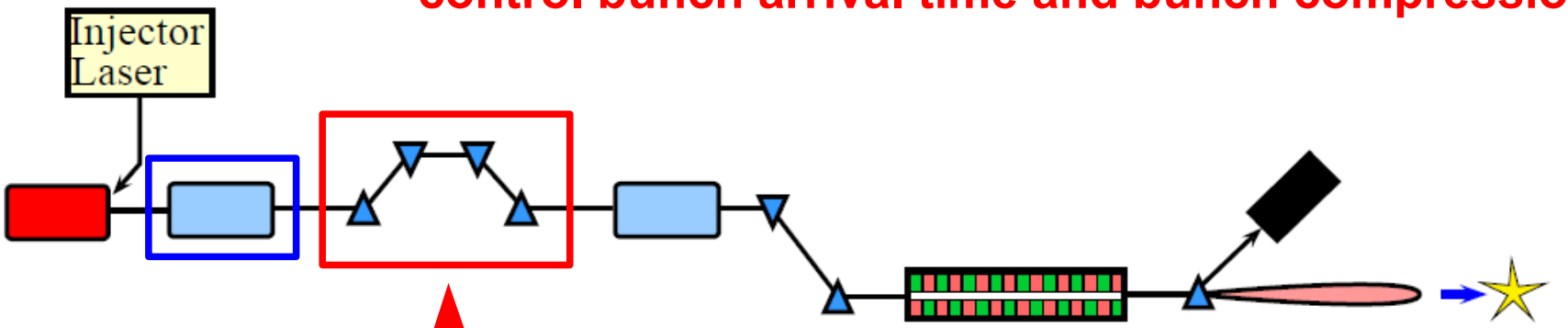
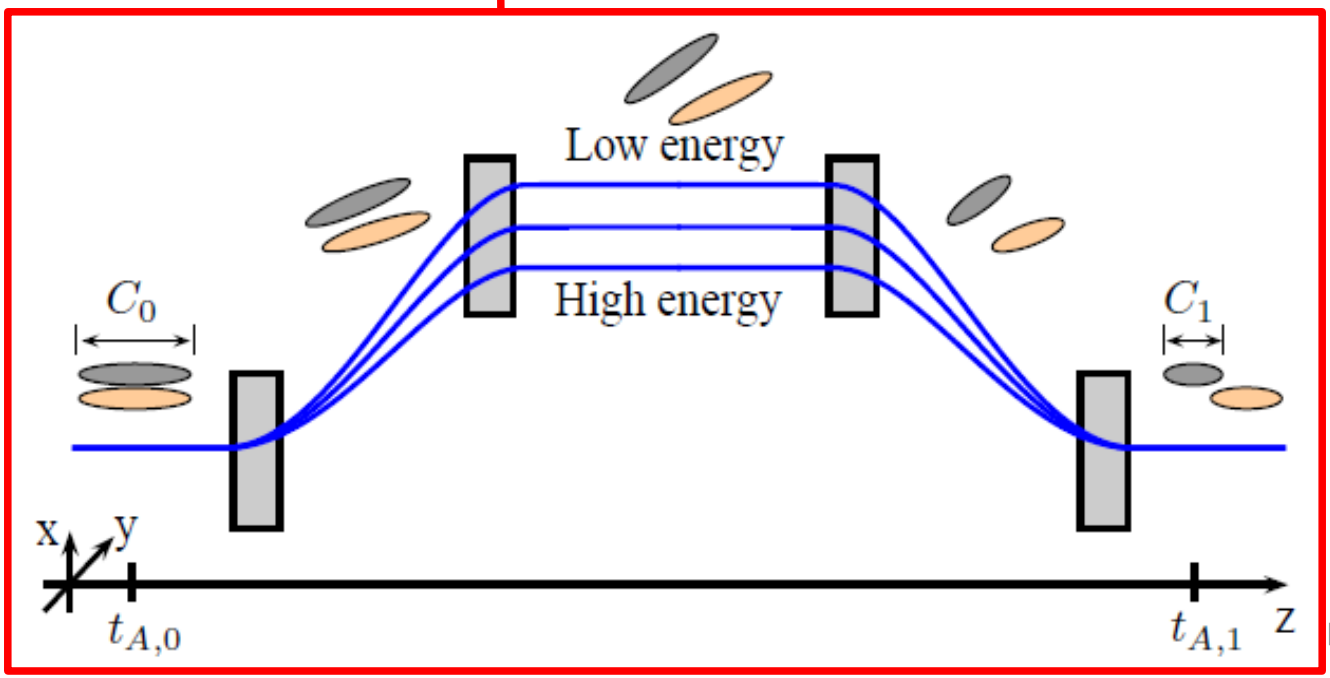
Bunch Arrival Time and Compression Feedback

Bunch energy modulation upstream of BC to
control bunch arrival time and bunch compression

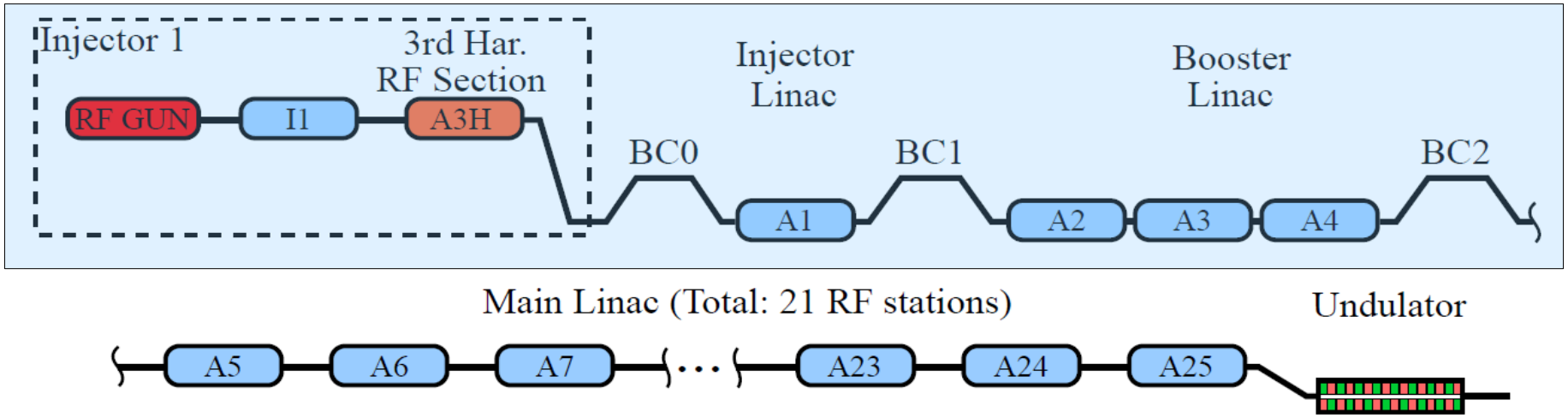




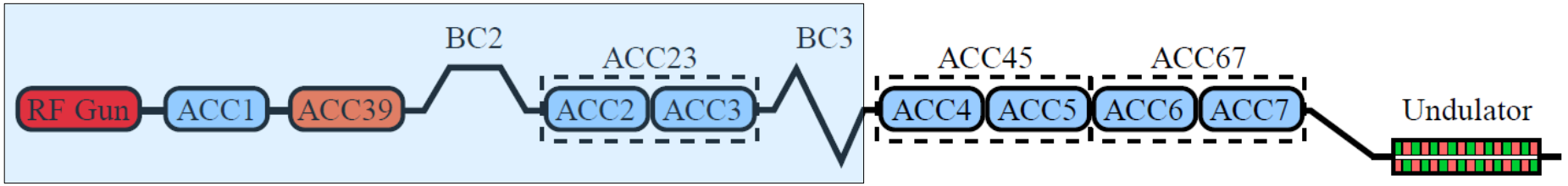
Adjust RF-field amplitude and phase,
→
mean bunch energy and
energy distribution within a bunch

Linear Accelerators at DESY in Hamburg

European XFEL – currently under construction

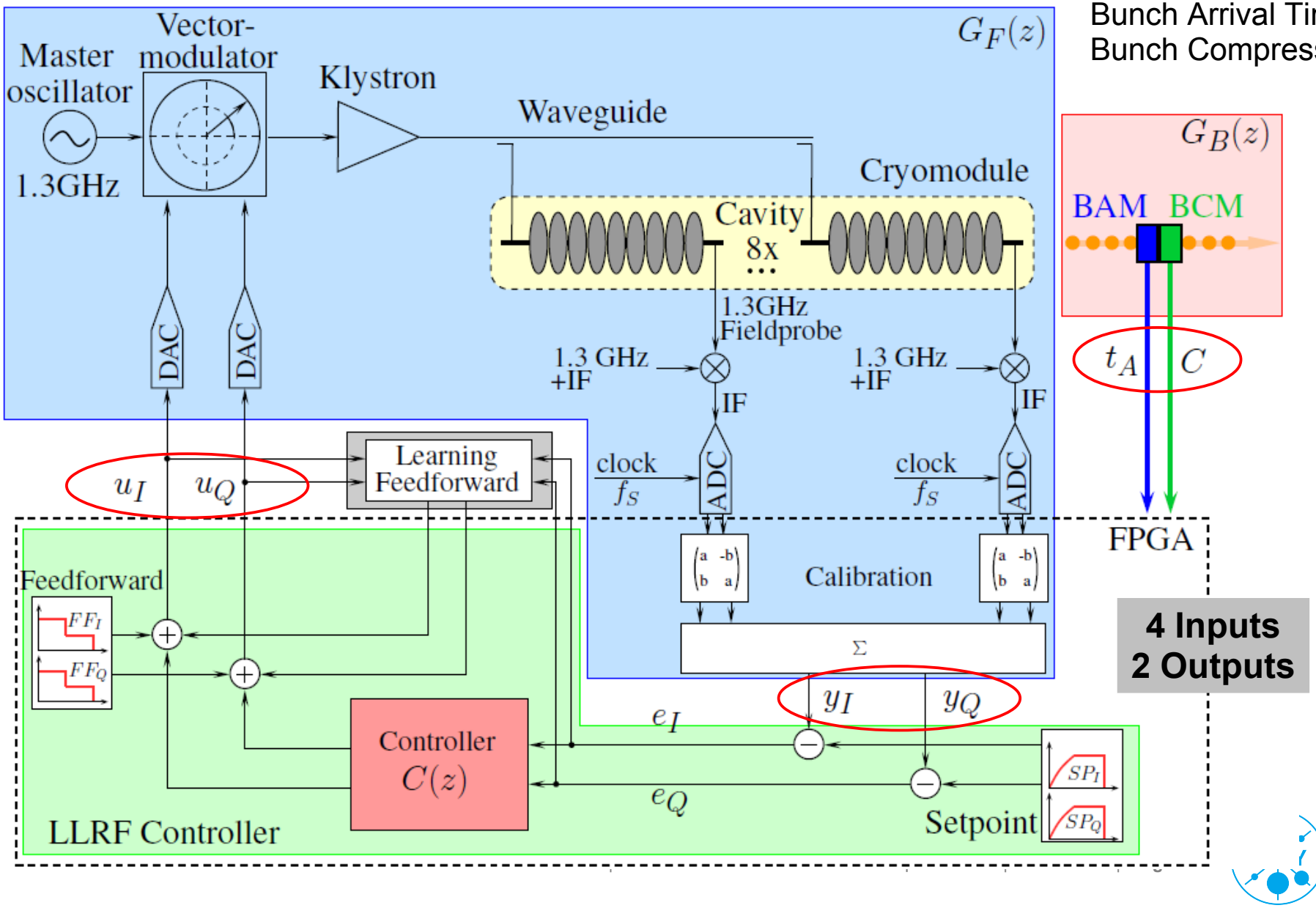


FLASH – in operation (test bench for XFEL)



Blue box: arrival time and compression feedback

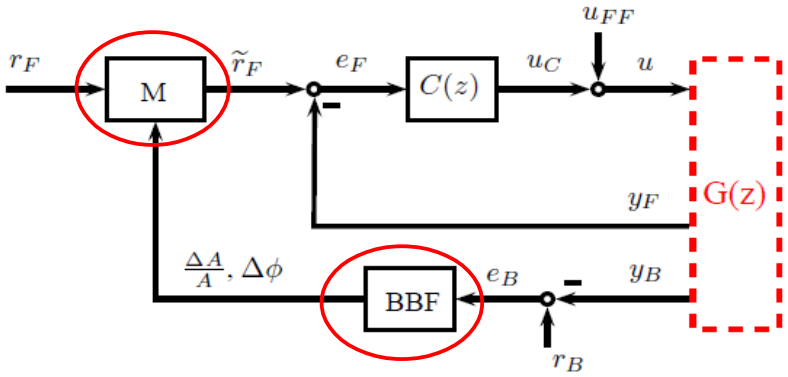
System Overview – FLASH and XFEL



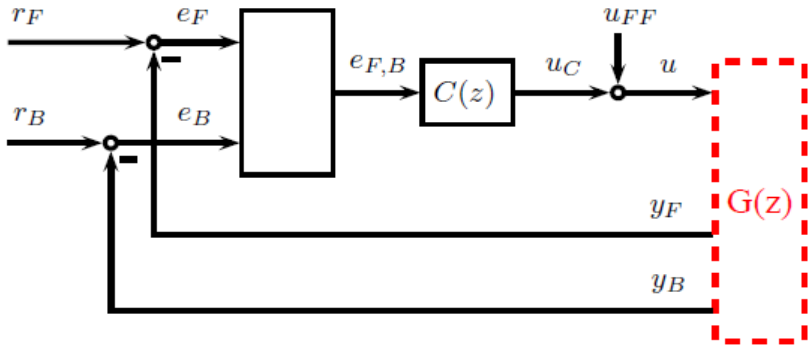
Bunch Arrival Time and Bunch Compression Feedback

Possibilities of beam-based feedback (not complete)

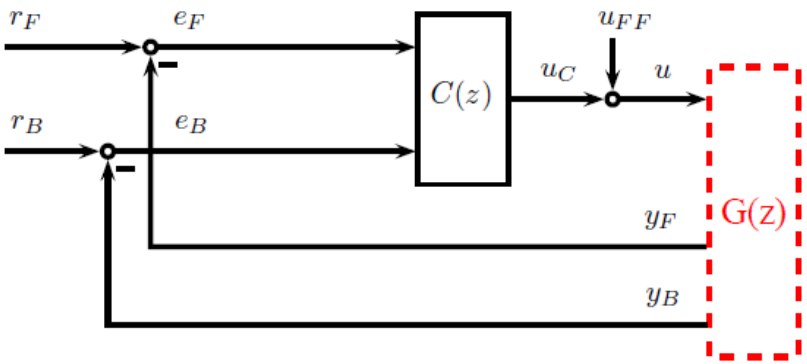
1) Set-Point Adaptation



3) RF field and beam error combination



2) Extended Controller



1) Good if latency of beam-based signals is larger than the latency for RF field signals [M...Modulation, BBF...maps beam errors to RF-field errors]

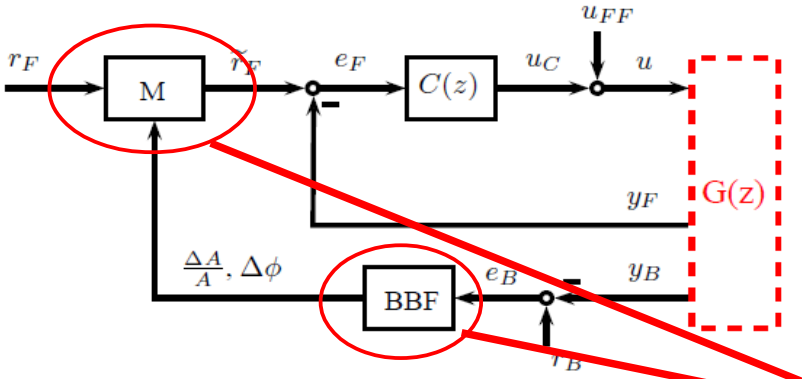
2) Good if the dynamic behavior for the beam-based signals and RF field signals differs

3) Good if the latency of signals are equal

Bunch Arrival Time and Bunch Compression Feedback

Possibilities of beam-based feedback (not complete)

1) Set-Point Adaptation



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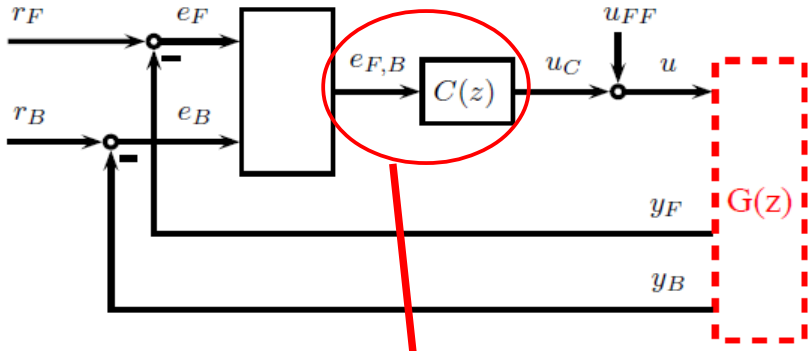
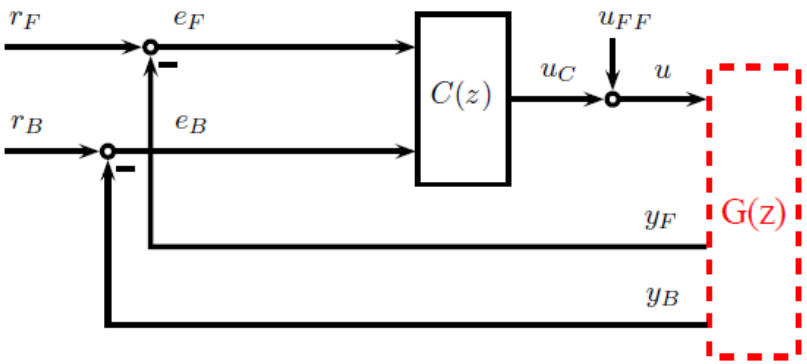
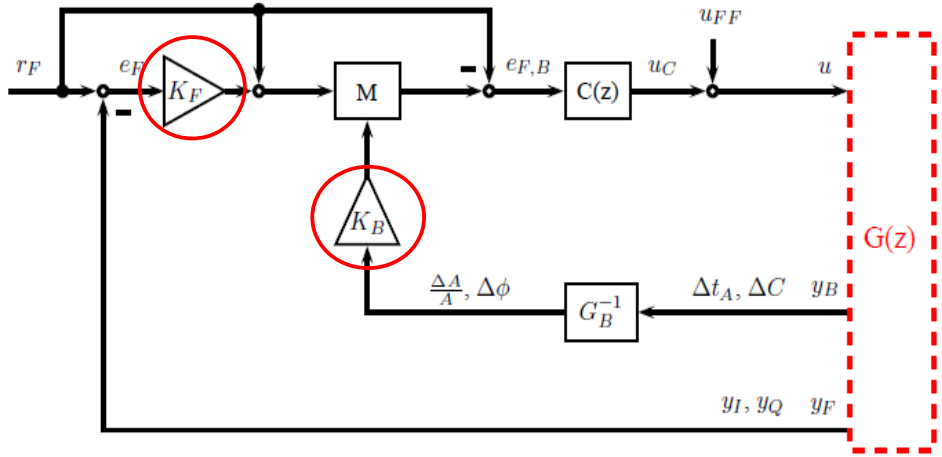


2) Extended Controller



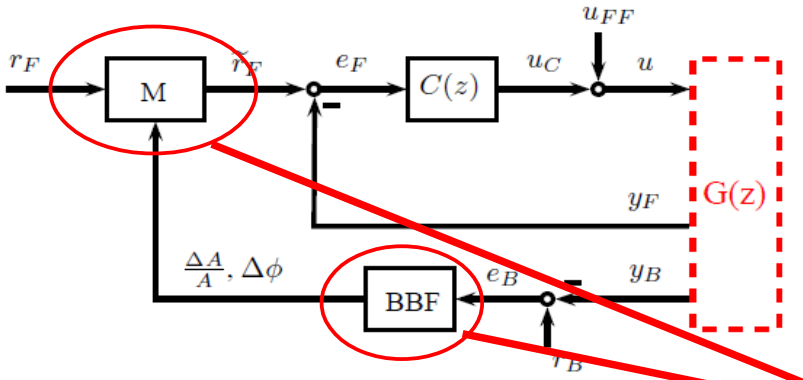
Final implementation at FLASH (simplified)



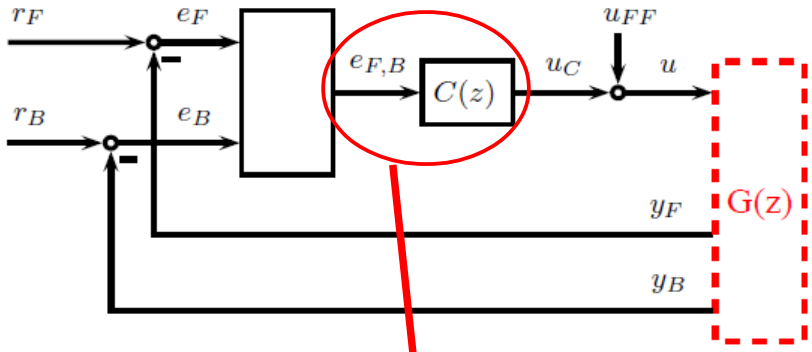
Bunch Arrival Time and Bunch Compression Feedback

Possibilities of beam-based feedback – not complete

1) Set-Point Adaptation

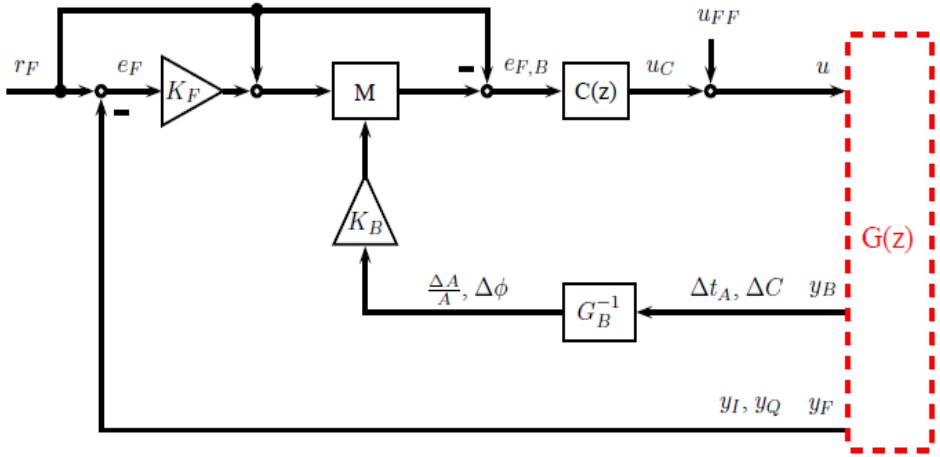


3) RF field and beam error combination

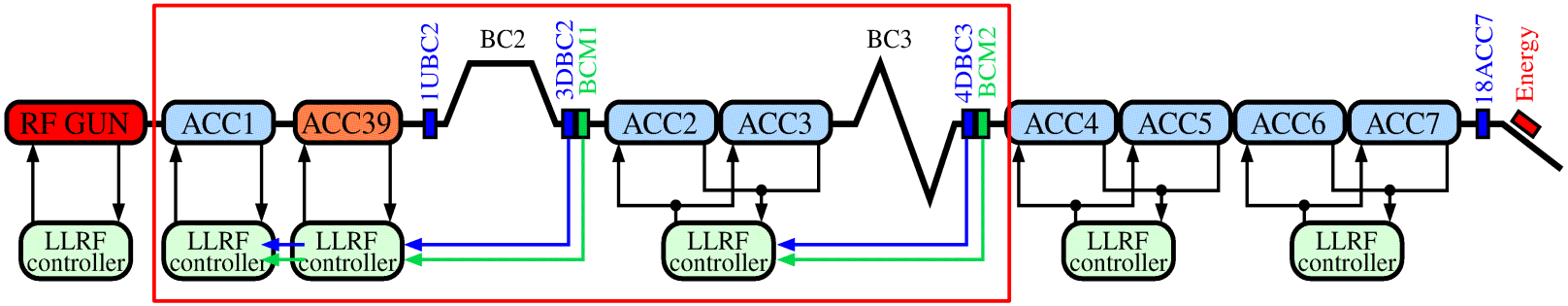


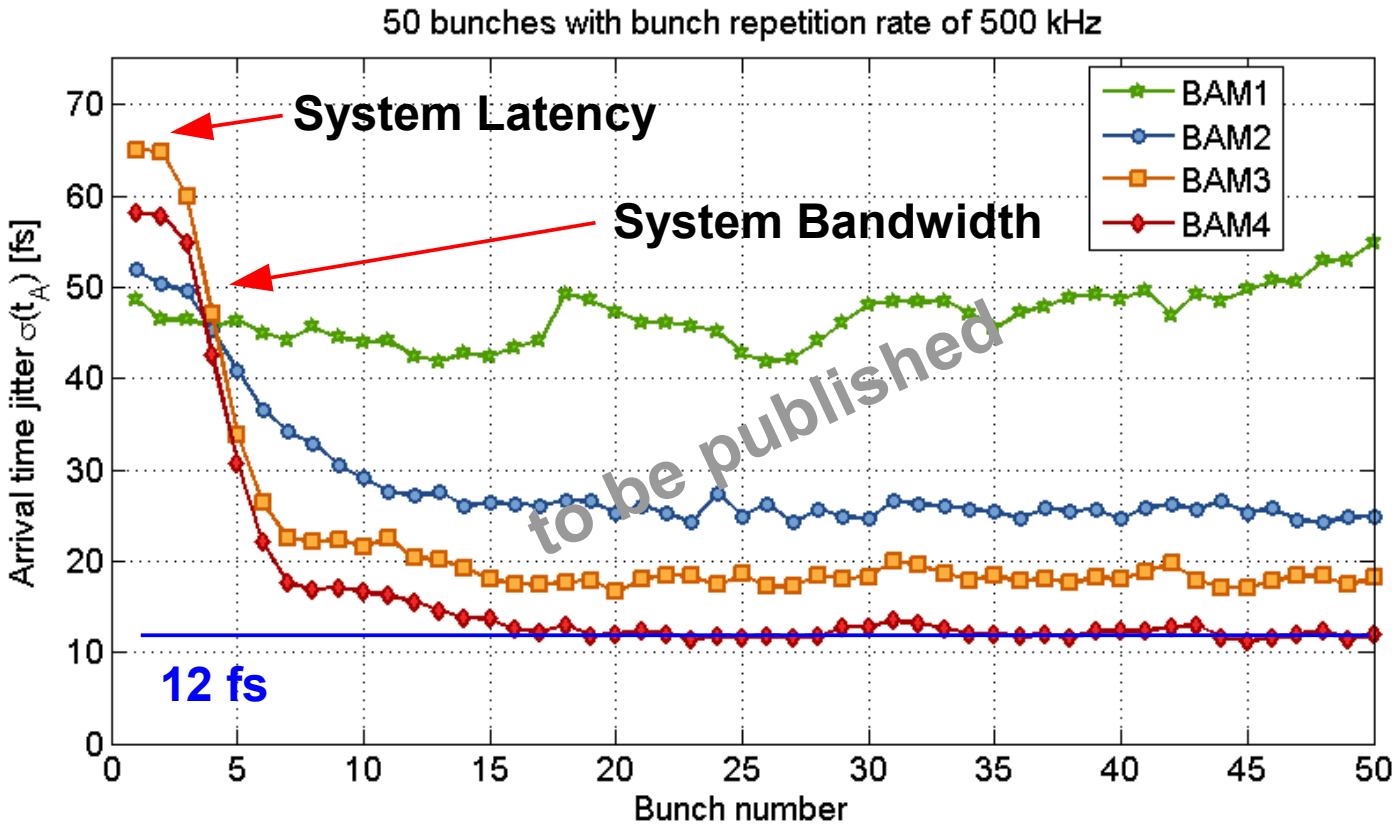
Proposed controller design, if:
- dynamic behavior of RF field and beam is similar
- latency of beam-based signals is smaller than latency of field signals
- beam-based signal resolution is larger than field signal resolution

Final implementation at FLASH (simplified)



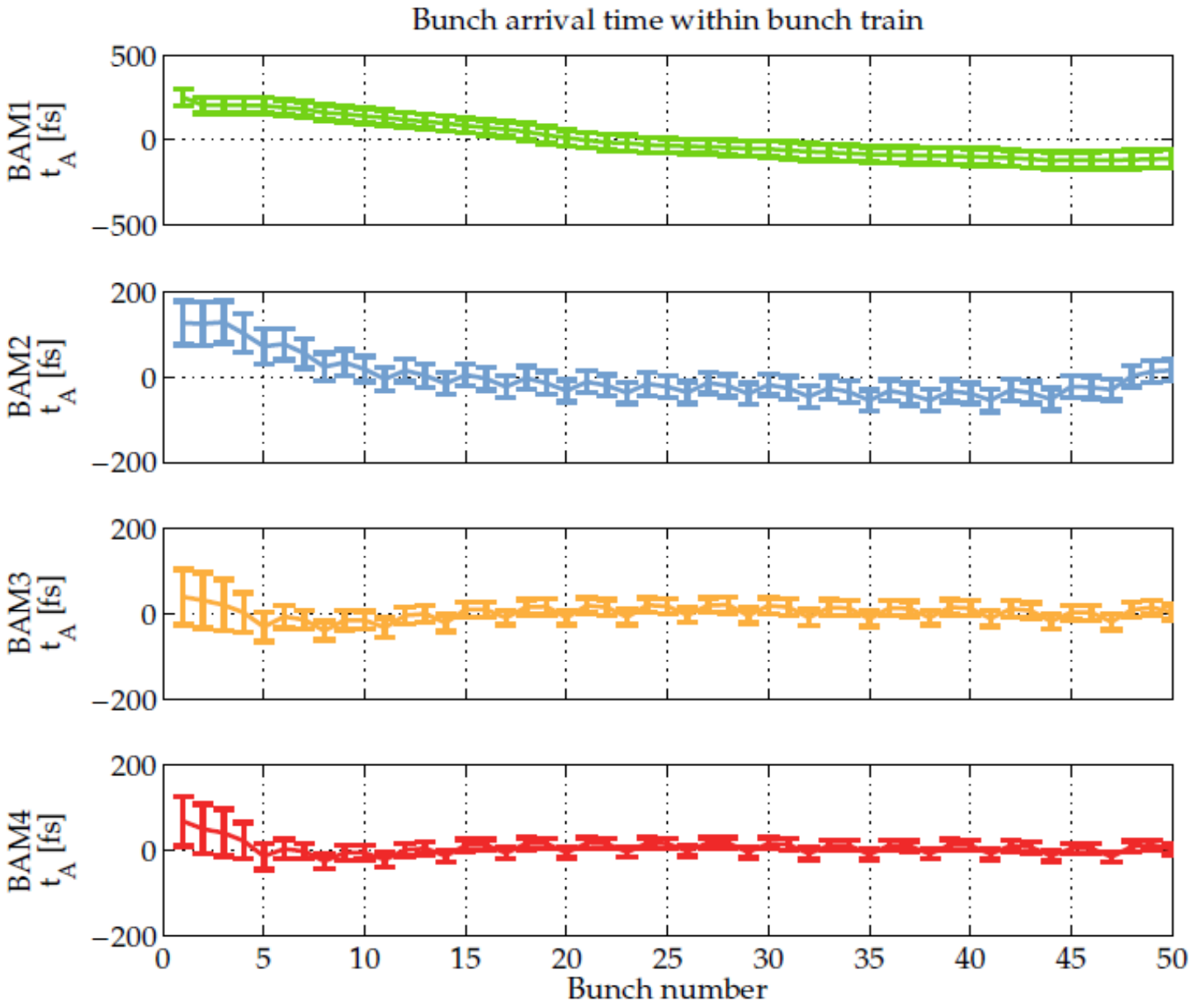
Fast Intratrain Controller at FLASH





- Bunch rep. Rate: 500kHz, 50 Bunche
- Proposed BBF
- Active on ACC1 and ACC23
- BAM4 is an out-of-loop measurement (highest resolution)

Iterative Learning Control

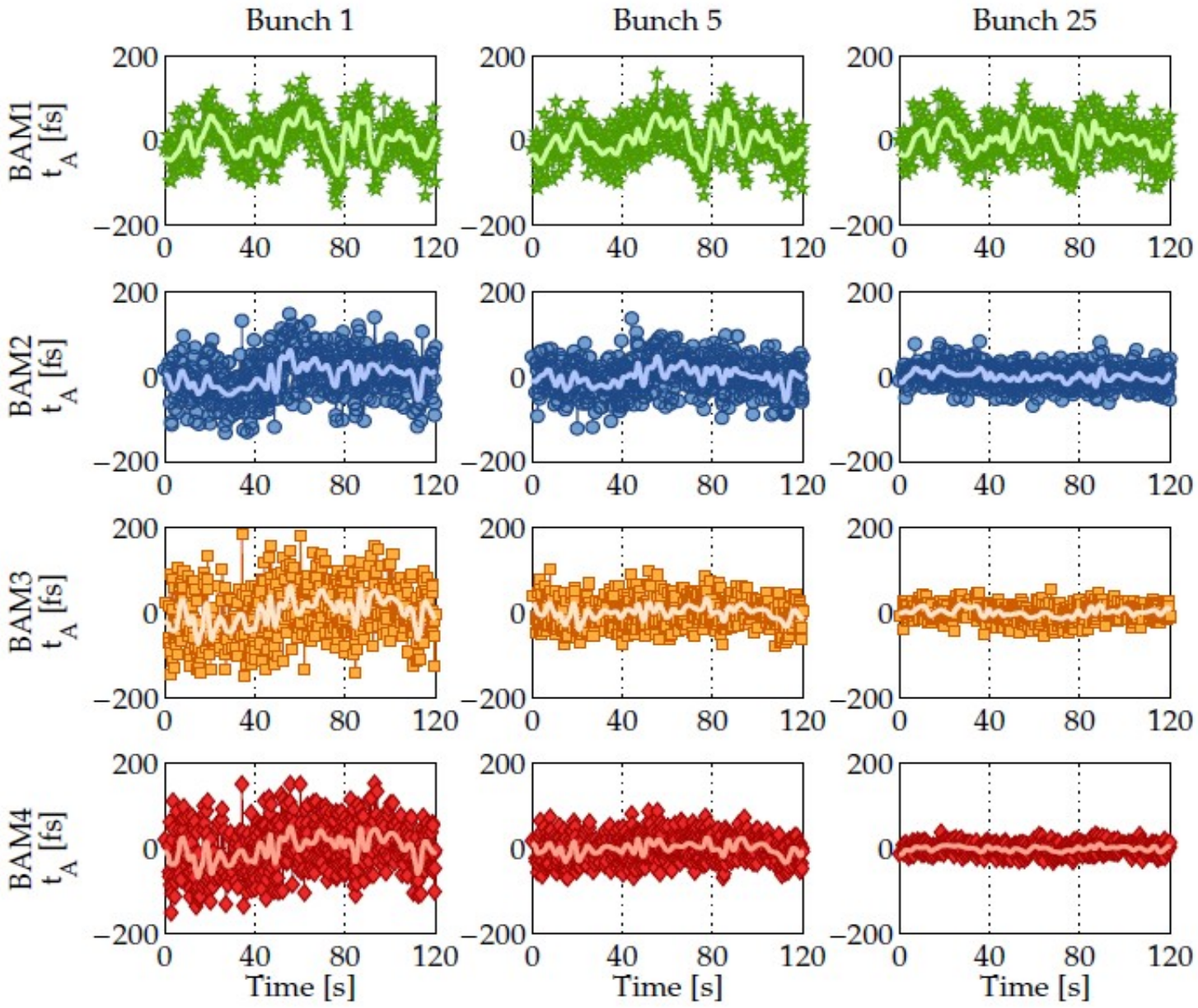


Pulse to Pulse Optimization

50 Bunches, Bunch rep. Rate: 500kHz

Iterative Learning Control reduces repetitive errors from pulse to pulse

Slow Feedback by Adjustment of RF Amplitude and Phase



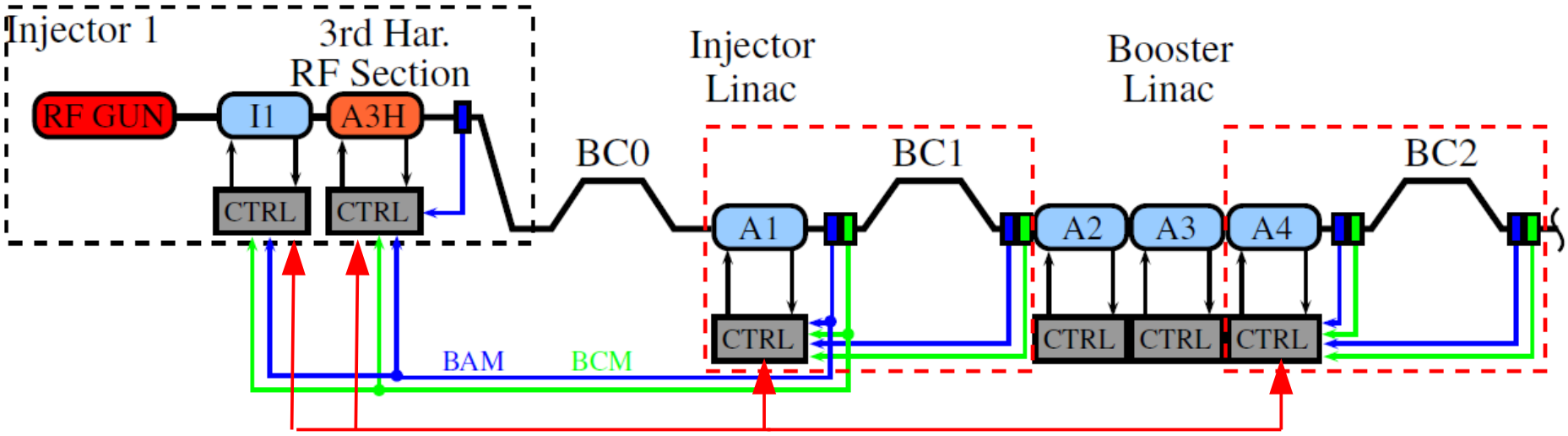
Drift Compensation

50 Bunches,
500 kHz,
#1: no BBF
#5: partly BBF
#25: full BBF

Slow RF-Feedback minimizes long-term drifts by adjusting RF-field amplitude and RF-field phase

Bunch Arrival Time and Compression Feedback for XFEL

Location of Bunch Arrival Time Monitor and Bunch Compression Monitor used for Beam-Based Feedback

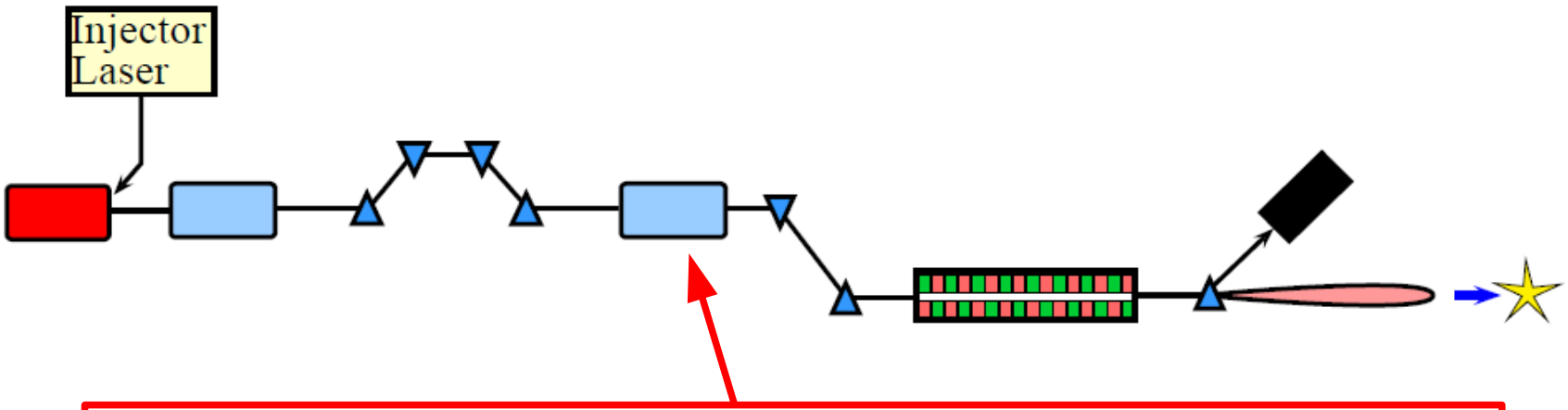


1st section (BC0) is similar to FLASH

2nd and 3rd section (BC1 and BC2) are considered as **enclosed subsystems** by controlling the difference between signal before and after bunch compressor; i.e. iff latency is zero → **observer/predictor-based control scheme with information exchange**

Contents

Bunch Arrival Time, Compression and Energy Feedback

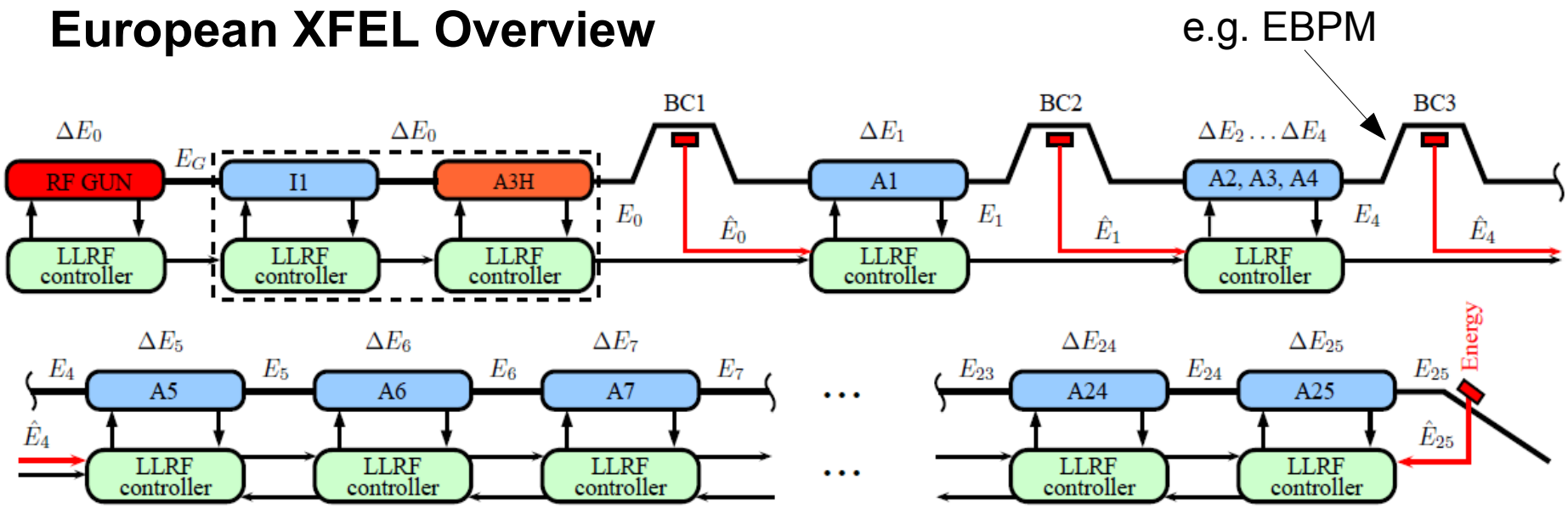


2) Bunch energy modulation downstream of the last BC to control the bunch energy

1) Slow energy errors by adjustment of RF-amplitude
2) Repetitive energy deviations by iterative learning control
3) How can we control fast energy errors???

Bunch Energy Feedback

European XFEL Overview



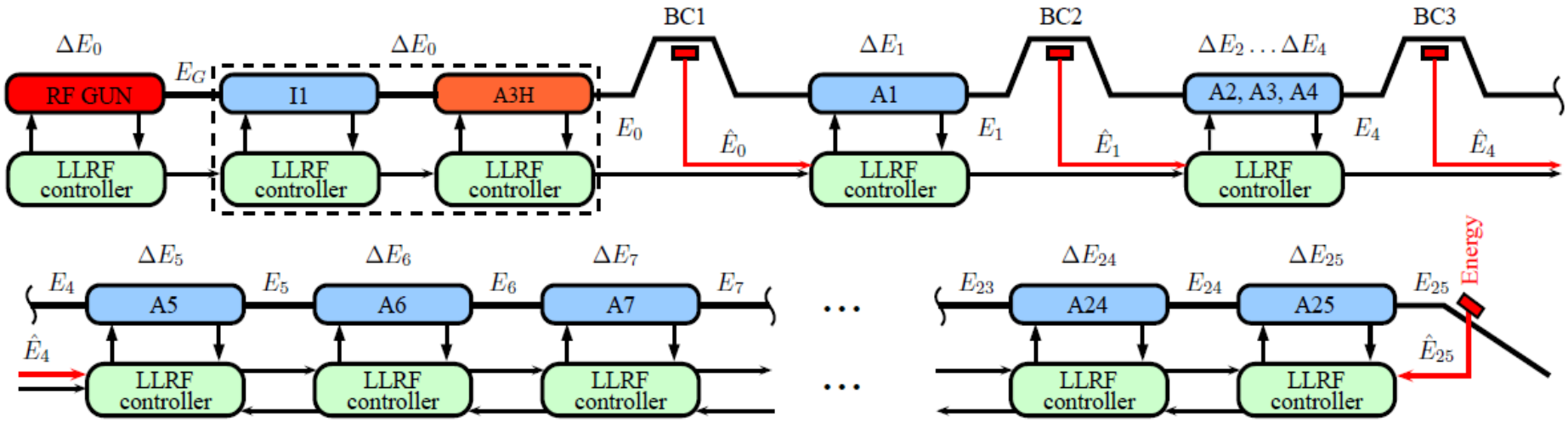
Main Linac for Bunch Energy Feedback

- LLRF controller interconnection
- 2 direct bunch energy measurements in main linac (initial and final)
- In between bunch energy must be estimated by energy gain
- Aim for local disturbance rejection by neighboring RF stations
  - Avoid to adjust all magnets downstream of energy error

Quench, Limiter, Pre-Limiter, ... → see Poster "LLRF Automation for XFEL"

Bunch Energy Feedback

European XFEL Overview



Target Energy: $$E(k,25) = E(k,4) + \sum_{s=5}^{25} \Delta E(k,s)$$

Energy Gain at Time k and Location s:

$$\begin{aligned} \Delta E(k,s) &= E(k,s) - E(k,s-1) \\ &= q \cdot A(k,s) \cdot \cos(\phi(k,s)) \\ &= q \cdot y_I(k,s) \end{aligned}$$

→ **Model-based approach**

Bunch Energy Feedback

D'Andrea, R. and Dullerud, G. E. (2003). Distributed control design for spatially interconnected systems. *IEEE Transactions on Automatic Control* 48(9), 1478–1495.

- Homogenous chain of subsystems
- Result: Controller by solving problem (LMI) for single subsystem

$$\begin{bmatrix} x(k+1,\mathbf{s}) \\ \begin{bmatrix} w_+(k,\mathbf{s}) \\ w_-(k,\mathbf{s}) \end{bmatrix} \\ z(k,\mathbf{s}) \\ y(k,\mathbf{s}) \end{bmatrix}_{x_0(\mathbf{s})} = \begin{bmatrix} A_{\mathbf{TT}} & A_{\mathbf{TS}} & B_{\mathbf{T},xd} & B_{\mathbf{T},xu} \\ A_{\mathbf{ST}} & A_{\mathbf{SS}} & B_{\mathbf{S},wd} & B_{\mathbf{S},wu} \\ C_{\mathbf{T},z} & C_{\mathbf{S},z} & D_{zd} & D_{zu} \\ C_{\mathbf{T},y} & C_{\mathbf{S},y} & D_{yd} & D_{yu} \end{bmatrix} \cdot \begin{bmatrix} x(k,\mathbf{s}) \\ \begin{bmatrix} v_+(k,\mathbf{s}) \\ v_-(k,\mathbf{s}) \end{bmatrix} \\ d(k,\mathbf{s}) \\ u(k,\mathbf{s}) \end{bmatrix}$$

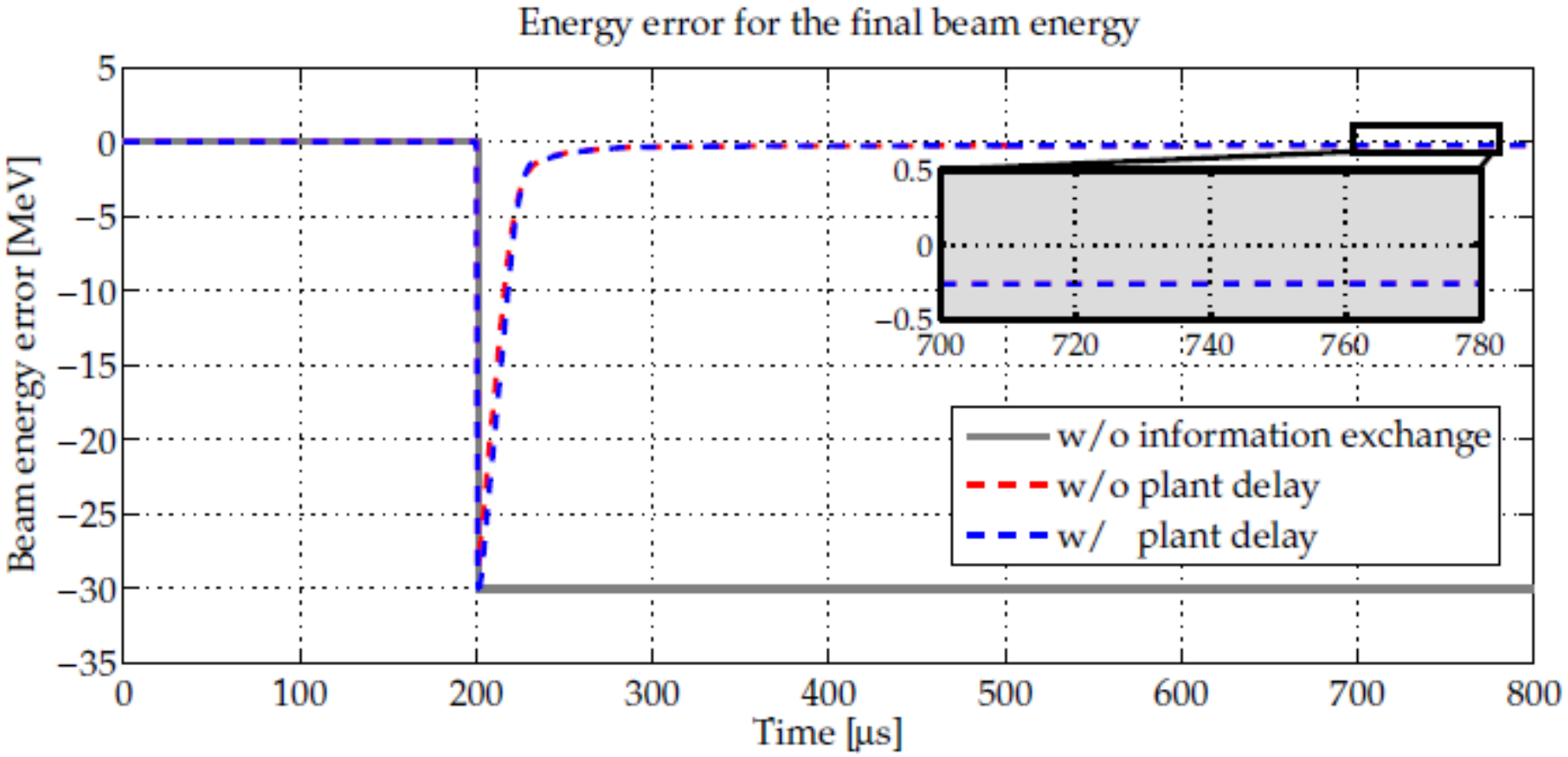
Interconnected state space model with:

temporal states T,k and spatial states S,s;
v input from neighbors, w output to neighboring LLRF controller;
d,z performance channels for loop shaping;
u input to vector-modulator, y is vector-sum

Controller inherits plant structure → interconnected controller

Bunch Energy Feedback

Simulation: Induced energy error of 30 MeV (2‰ for 17.5 GeV) in RF Station 13
Step like error (quench → limiter activated) as extrema
(will not occur, but is a broad band signal)



Target beam energy is almost recovered after short transition time

Bunch Energy Feedback

Simulation: Induced energy error of 30 MeV (2‰ for 17.5 GeV) in RF Station 13
Step like error (quench → limiter activated) as extrema
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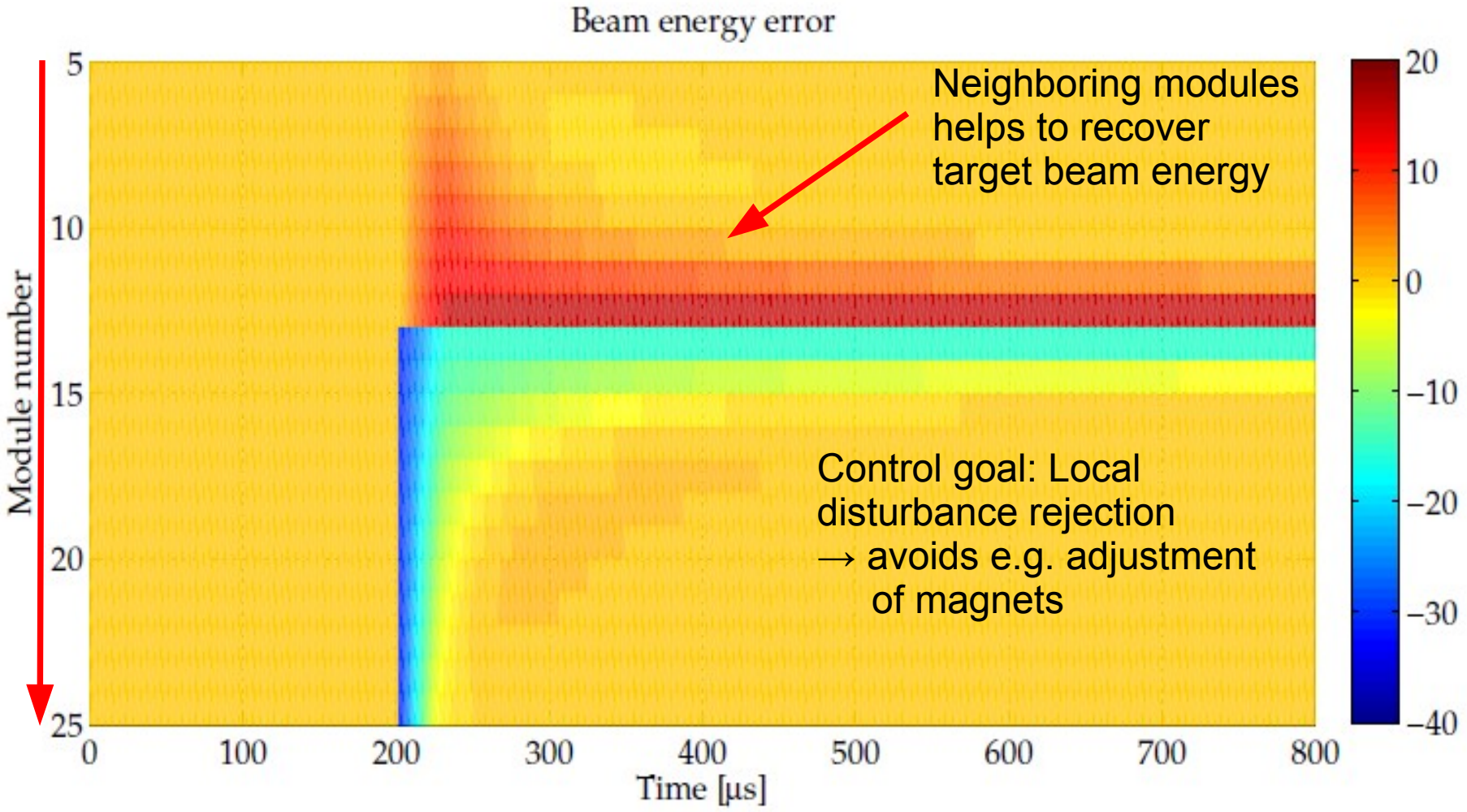


Conclusion and Outlook

Conclusion:

- Beam-based feedback for bunch arrival time, compression and energy
- Intratrain beam-based feedback
  - > Within injector/booster part as cascaded control structure (arrival time and compression)
  - > Within main linac as distributed control scheme (energy)
- FLASH shows significant improvements in bunch arrival time and bunch compression jitter

Outlook:

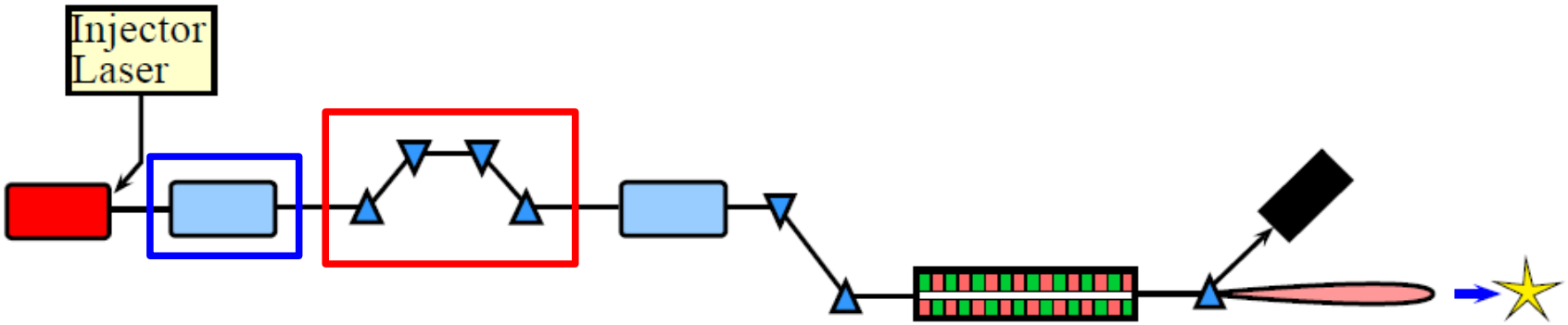
- Further improvements using a NC cavity at FLASH (~2015)
- LLRF automation, exception handling, energy management, …

  --> See Poster “LLRF Automation for XFEL”

Thank you for your attention!

sven.pfeiffer@desy.de

Bunch Arrival Time and Compression Feedback



Properties of Bunch Compressor for single electrons

Orbit changes in x and y are neglectable

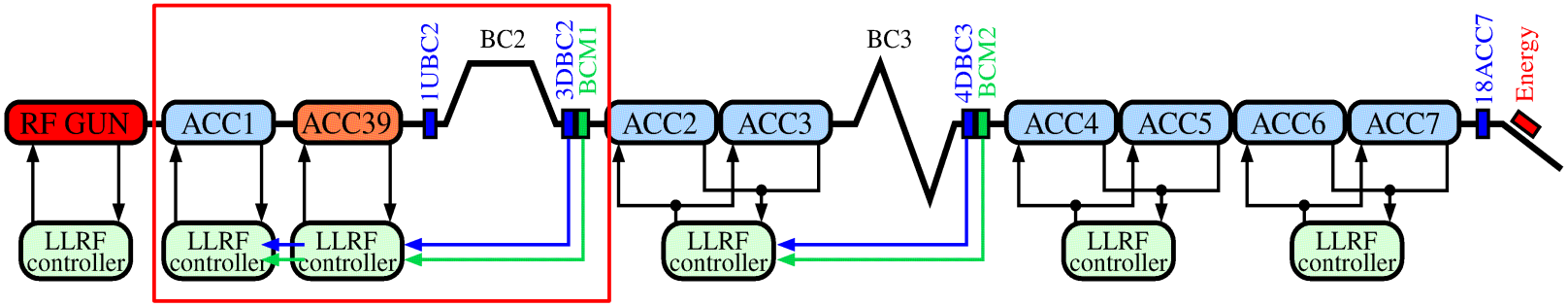
Path length changes through BC

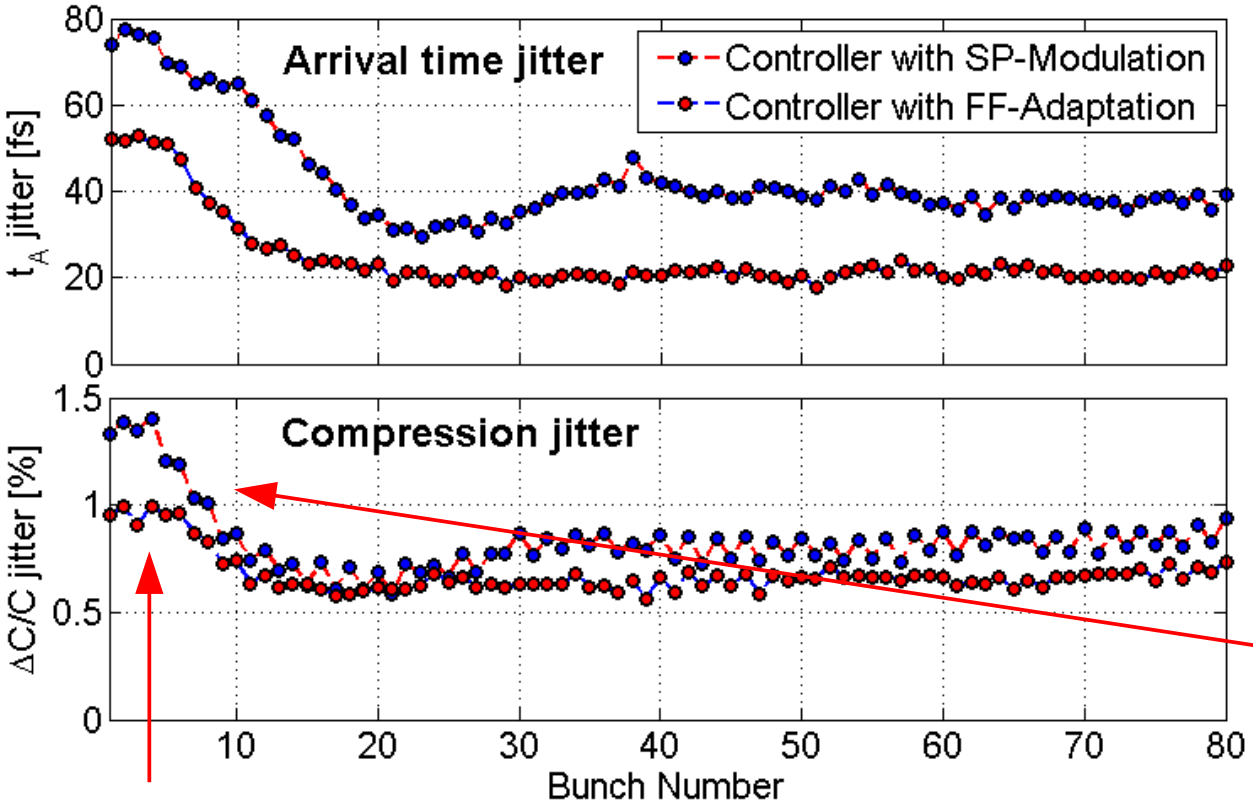
Energy deviations

$$\begin{bmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ l_f \\ \delta_{E,f} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ \cancel{R_{51}} & \cancel{R_{52}} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ x'_i \\ y_i \\ y'_i \\ l_i \\ \delta_{E,i} \end{bmatrix}$$

$$\Delta t_A = \frac{(z_f - z_i)}{v_e} = \frac{\Delta z}{v_e} = -\frac{R_{56}\frac{\Delta E_i}{E_{0_i}}}{v_e}$$

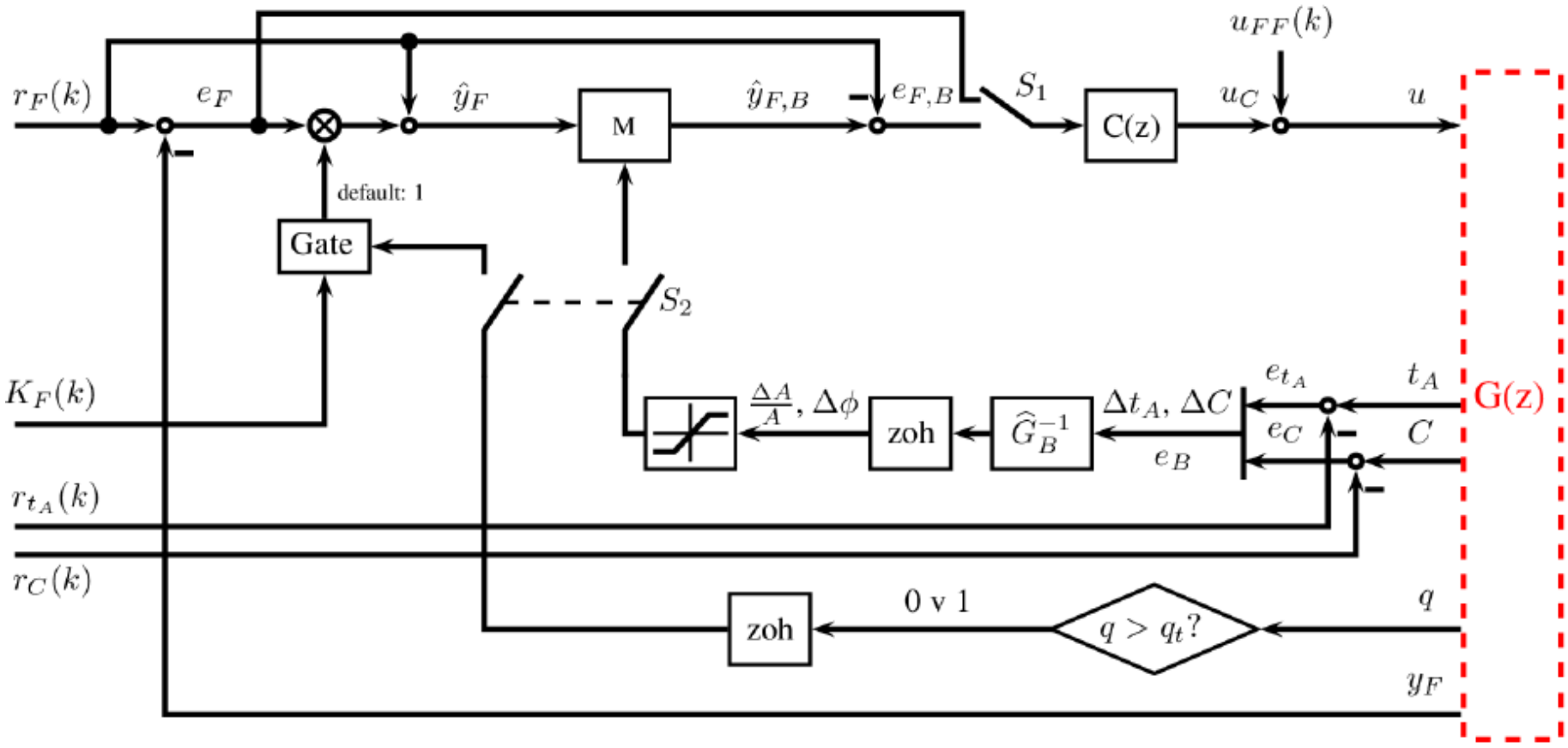
Fast Intratrain Controller at FLASH





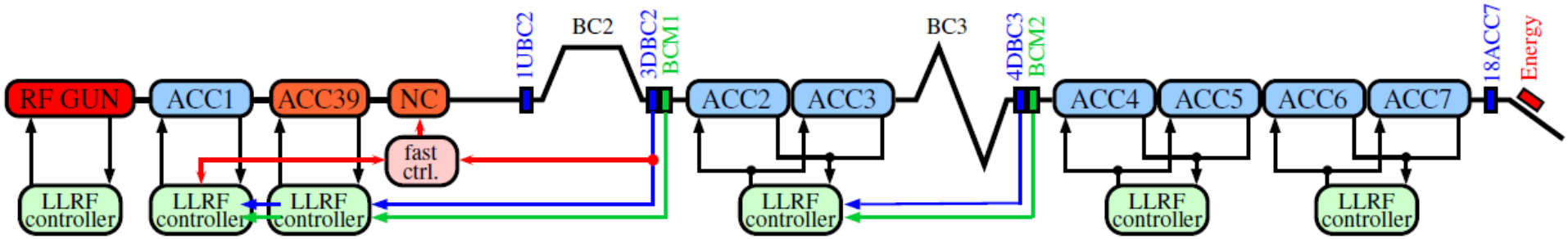
- Bunch rep. Rate: 1MHz, 80 Bunche
- BBF - FF Adaptation
- Active on ACC1
- Jitter after BC2
- BBF - ACC23 off

Beam-Based Feedback Implementation



DESY

Planned Extension at FLASH - 2015 (NC Cavity)



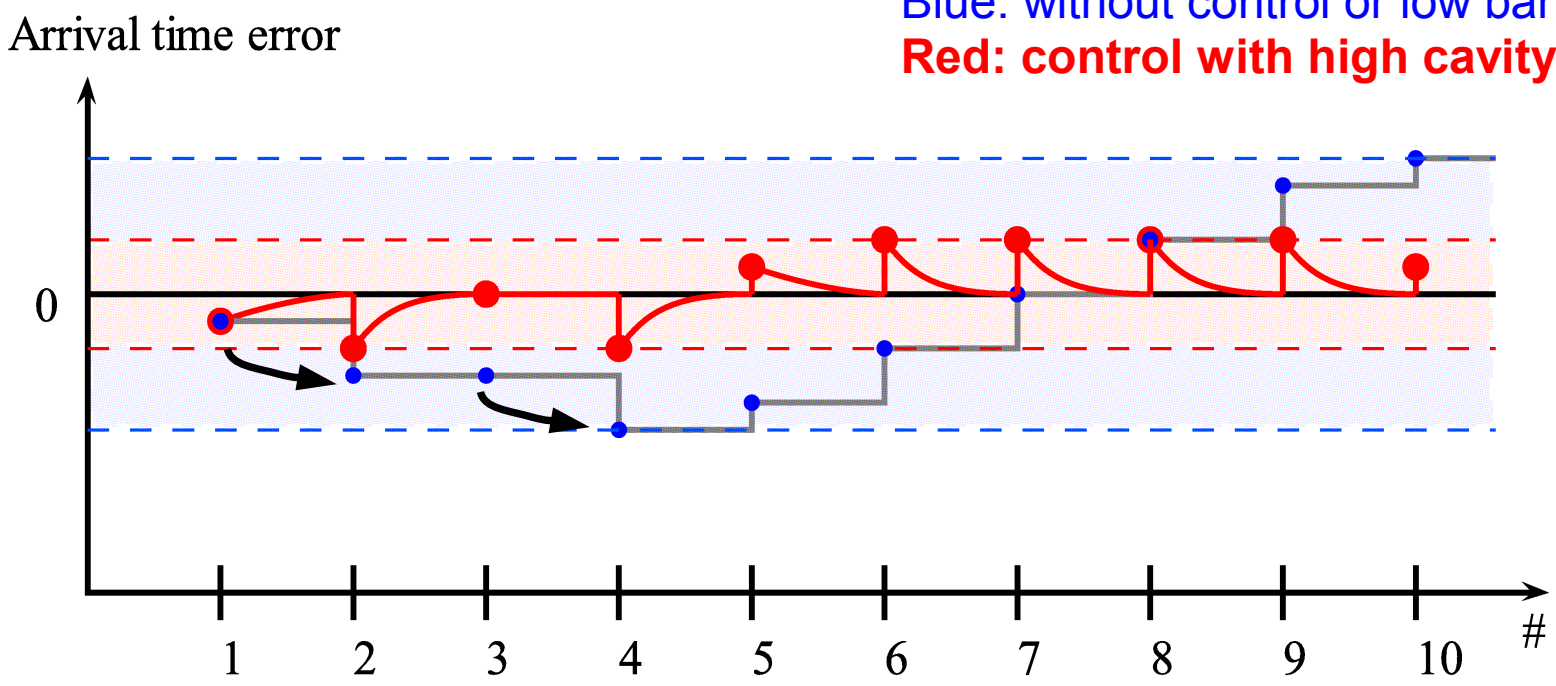
Closed loop bandwidth r(t) → y(t)

SC ~ 41kHz

NC ~ 690kHz

Blue: without control or low bandwidth

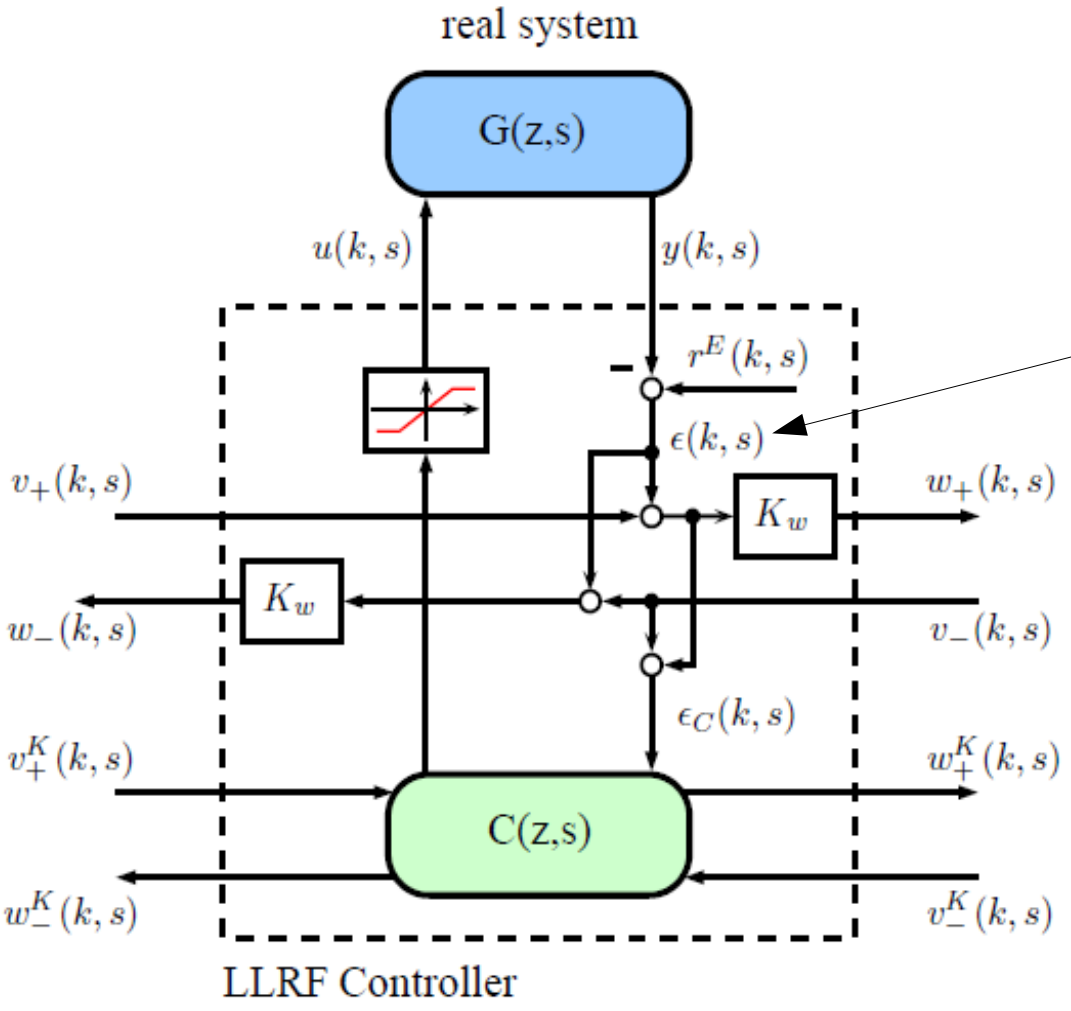
Red: control with high cavity bandwidth



Max. error is a function of BW (and loop delay)

Bunch Energy Feedback – Implementation RF Station

Model-Based Controller Design by sophisticated Tools



u(k,s) … to Vector Modulator
y(k,s) … Vector-Sum

Energy gain error

Energy gain error is weighted and exchanged to both neighboring LLRF controller

Controller states are exchanged → ensures a stable operation

Bunch Arrival Time Monitor

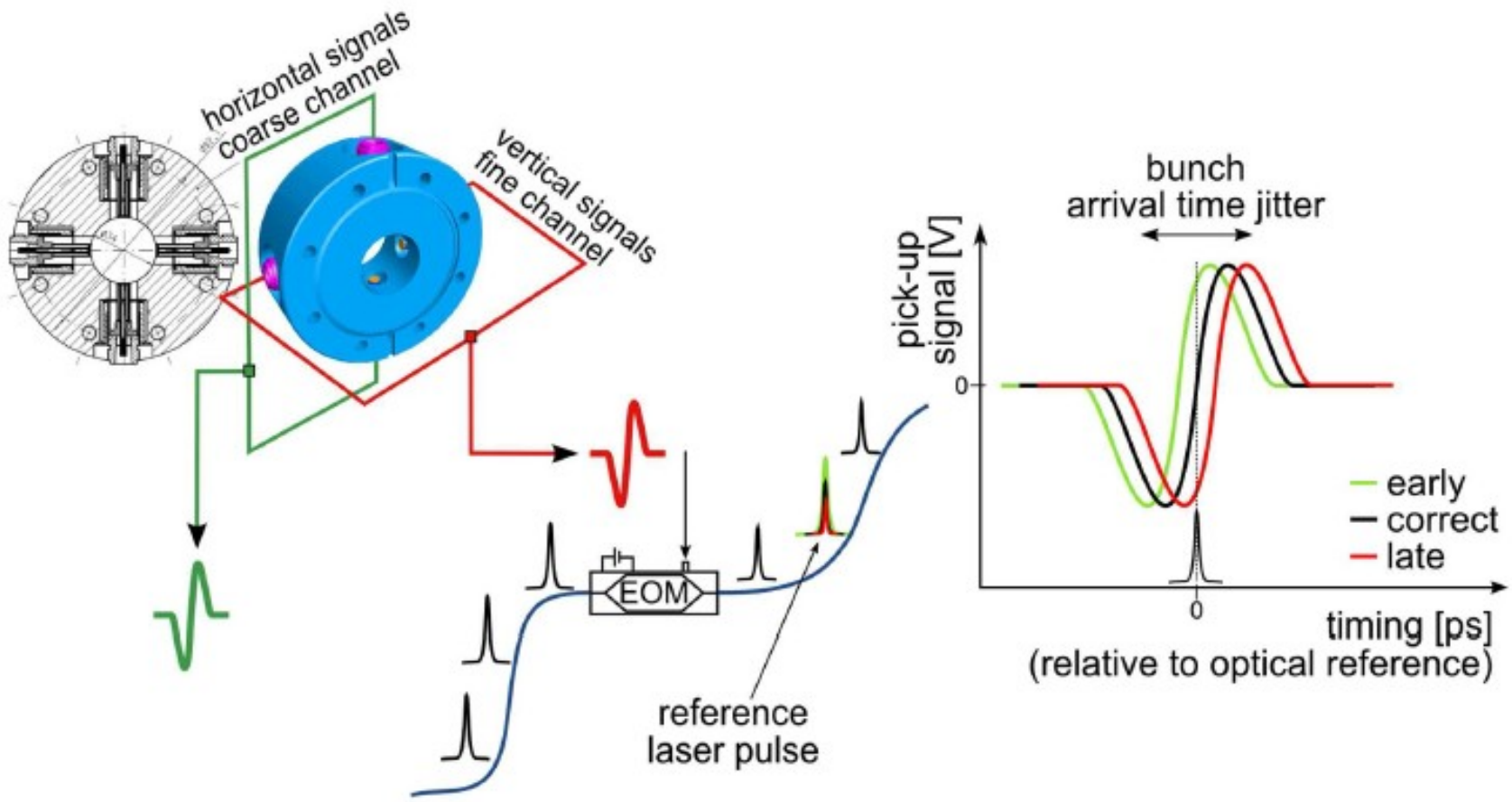


Figure 2.4.1: BAM principle [Bock, 2012].

Arrival time changes of the voltage zero-crossing relative to the optical reference are transferred into an amplitude modulation which is detected.

Bunch Compression Monitor

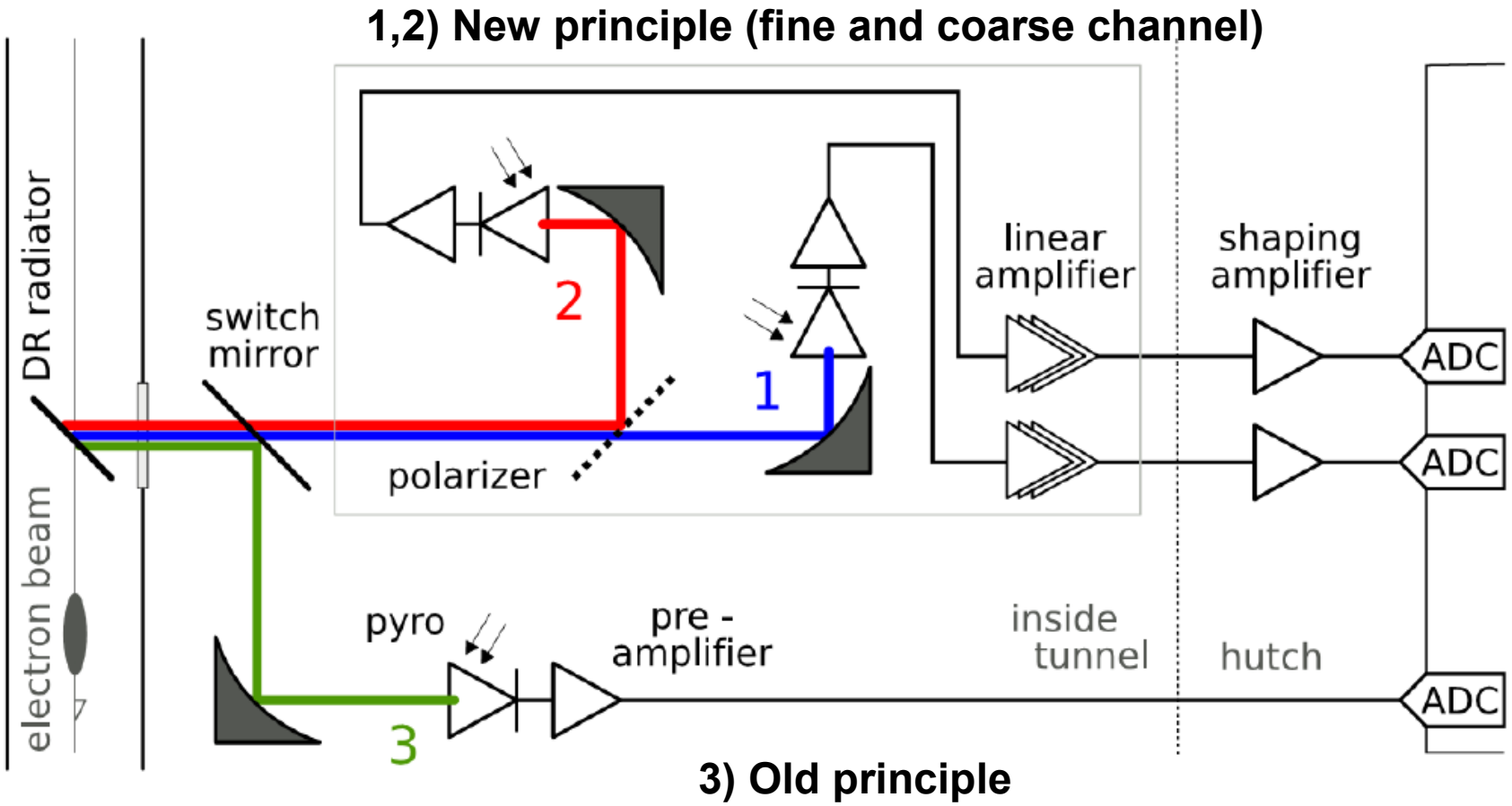
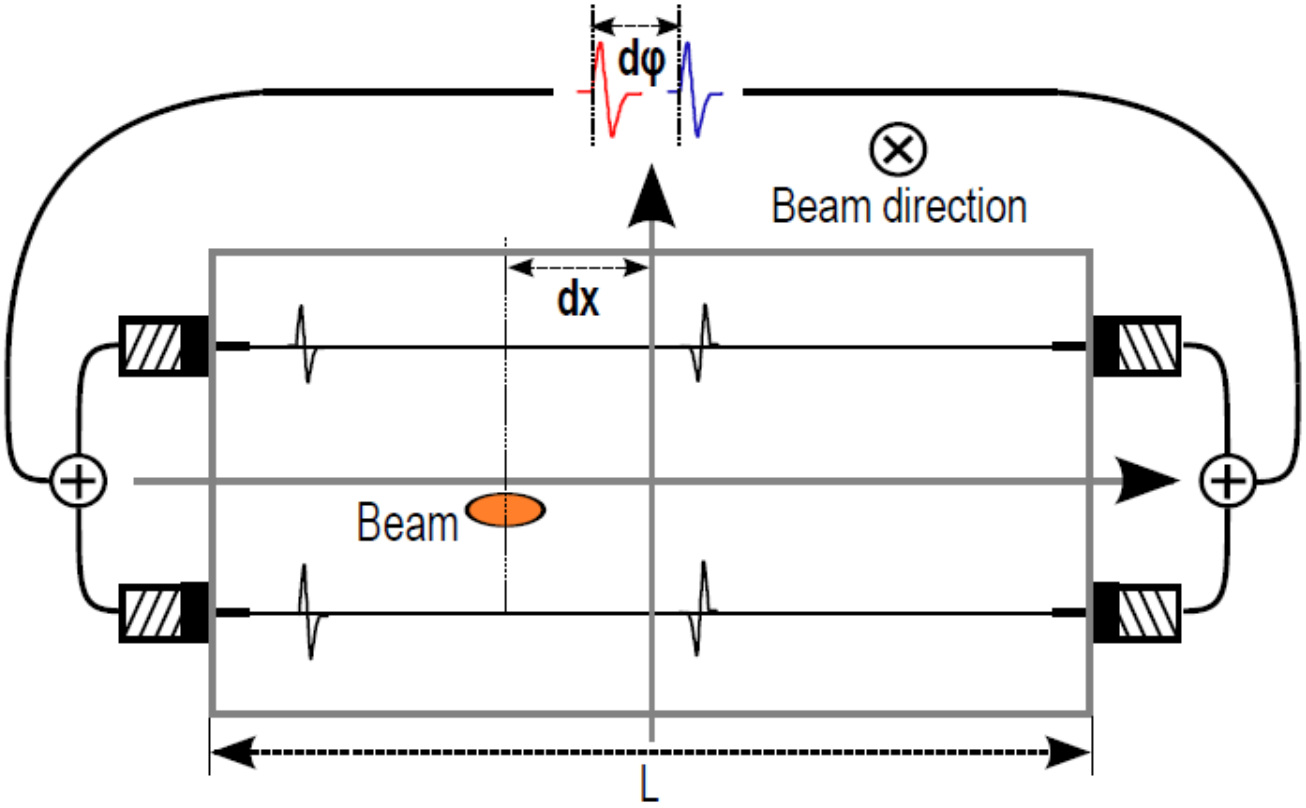


Figure 2.4.2: BCM principle [Behrens et al., 2010].

Measure the bunch peak current behind a bunch compressor

Energy Beam Position Monitor

Within Bunch Compressor



Added to reduce the dependence on the y-direction

dφ ~ dx ~ dE

Figure 2.4.3: EBPM principle [Mavrič et al., 2012].